A comparative study of different rapid visual survey methods used for seismic assessment of existing buildings

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A comparative study of different rapid visual survey methods used for seismic assessment of existing buildings

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ABSTRACT

Determination of seismic safety of existing buildings is a time consuming and challenging process. Instead, rapid survey methods were developed which identify deficient structures from a large building stock in a city or town. This paper presents a comparison and critical review of existing rapid visual survey methods used for seismic assessment of existing reinforced concrete buildings. The study focuses on rapid visual survey methods developed for the safety assessment of reinforced concrete buildings in the Indian subcontinent and a widely used method in the United States.

Comparison is carried out in various ways. Initially, a direct comparison is made based on vulnerable parameters and damage grades proposed by each method. Later, a scoring system is developed to highlight the differences and rank the selected methods. This system considers the general description, physical parameters, and damage description. Finally, as a case study, a rapid visual survey was conducted on 100 reinforced concrete buildings in each of the three cities (i.e., Pithoragarh, Gangtok, and Agartala) in India. These cities have different seismic, geological, and topographical conditions. The results show that all five methods give different outputs for the same sample surveyed buildings in each city. It was observed that there are many uncommon vulnerability parameters amongst each selected method. The results show a considerable variation in the weights assigned to each vulnerable parameter in all five methods.

1. Introduction

In the past few decades, there has been a dramatic increase in human casualties and economic loss due to natural catastrophes worldwide [1]. Among these natural catastrophes, earthquakes have been the most disastrous calamity. The reasons for these increased losses are many, but the most apparent reason is population. The rapidly growing urban population has created a massive demand for the construction industry. Developing countries face city planning and construction quality problems because of a lack of expertise, imprecise legislation, inadequate funds, and unplanned urbanization [2]. Such chaotic development has led to buildings' poor and unexpected behaviour during earthquakes, causing severe damage, and sometimes even buildings collapse.

According to the past earthquake database, the 2011 Tohoku earthquake resulted in 15,000+ casualties, and 120,000 buildings were collapsed [3,4]. The 2010 Haiti earthquake resulted in 60,000+ casualties, and nearly 280,000 buildings were collapsed [5]. In India, the 2005 Kashmir earthquake caused almost 1500 deaths and 400,000+ collapse of buildings [6,7]. Whereas the 2001 Bhuj earthquake caused 13,000+ deaths and 200,000+ destruction of buildings [7,8]. Further, the financial loss caused by Van earthquake in 2011 in Turkey was $2.2 billion, whereas the loss was $1.7 billion when the Sikkim earthquake stuck in India in the same year [9]. It has been observed during past earthquakes that older buildings have suffered more damage; therefore, old constructions are at significant risk even to moderate earthquakes. These massive damages caused by an earthquake in most developing countries has underlined the need for seismic evaluation of a vast stock of existing building [10]. The assessment of potential damage and loss scenarios for future earthquake events is also equally essential in mitigating seismic risk [11].

Seismic risk combines three fundamental components: hazard, exposure, and vulnerability [12]. The hazard represents the likelihood of a given location experiencing a certain level of shaking; exposure represents the inventory of buildings exposed to a hazard, and vulnerability describes how the exposed assets will be affected by the hazard [13]. The rapid sprawling of the built-up areas, unplanned settlements, and the general rapid changes in modern and megacities heavily affect the space and time dependency of the exposure and vulnerability model

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[13]. The amount of resources spent on the vulnerability assessment of old buildings is justifiable; hence not only does a first-level assessment include building inspection, but it also can help in the identification of buildings for which a more detailed assessment is required [11].

The main objective in determining a building's earthquake safety is to give correct decisions on existing building stock by conducting the necessary inspections and evaluating existing buildings in advance of a possible earthquake [14]. But the assessment of a large number of buildings spread over a vast area is the biggest challenge. Therefore, it was felt necessary to develop a method that rapidly identifies most deficient or vulnerable buildings, which require further detailed evaluation or sometimes retrofitting [15].

Determining the seismic performance of existing buildings with the conventional code-based assessment procedure is costly and time-consuming, due to which "Rapid Visual Survey (RVS) Methods" were developed. Instead of code-based assessment procedures, these RVS methods can reduce the number of buildings, which have to be assessed with more detailed code-based assessment techniques [16]. It is also observed that there is increasing research in the same area [17]. RVS method requires significantly less time. The primary objective behind the development of this method is to minimize the resources needed for the evaluation of buildings in great numbers [18]. The method can be used for the safety assessment of buildings before the earthquake and after the earthquake. The safety assessment before an earthquake helps in understanding the earthquake risks that a city/town will face regarding the earthquake performance of houses. In contrast, assessment after an earthquake helps decide whether a building in the earthquake-affected area can be occupied or not [19,20]. Using the final score of RVS, buildings which require further preliminary and detailed evaluation can be easily identified. Such a quick assessment method is an essential tool for governments and decision-makers to allocate resources and mitigate earthquakes [17,21] optimally.

There are many rapid visual survey methods developed for safety assessment of buildings in past few decades (FEMA-154 [21,22]; NRCC [23]; Hassan and Sozen [24]; Gulkan and Sozen [25]; JBDPA [26]; Arya [27]; METU [28]; Sinha and Goyal [29]; Yakut [15]; Demartinos and Dritsos [30]; NZSEE [31]; Sucuoglu et al., [32]; Wang and Goettel [33]; Karabassi and Nollet [34]; Jain et al., [35,36]; P-25 [37]; Achs and Adam [38,39]; BMTPC [19,20]; Yadollahi et al., [40]; PERA [41]; Kaplan et al., [16,42]; Pardalopoulos et al., [43–45]). FEMA-154 method which was developed in 1988 has been further revised in the year 2002 and 2015.

The current study aims to compare the rapid visual screening (RVS) methods used for the safety assessment of existing reinforced concrete (RC) buildings. During the rapid survey of buildings in three different cities, it was observed that each method gives a different result for the same building. So, the second aim of the study is to find the reasons for the varying results. The comparison of selected methods is performed in various ways. At first, the comparison is made based on vulnerability parameters considered and the damageability grades used in each RVS method. After these simple and straightforward comparisons, methods were further compared using the arbitrary and multi-criteria-based decision-making (MCDM) approach. The final comparison is based on the results of each RVS method for which a rapid visual survey is conducted in three different cities in India.

Most of the available literature on the comparison of RVS methods focuses on the closeness of results of the method proposed by those authors with other available methods. The comparison at various levels presented in this paper helps to understand each RVS method's workability to find the shortcomings in the method and scope for improvement.

2. RVS methods

The motive behind the rapid visual survey method is to save and minimize the resources required for the safety assessment of buildings in great numbers. According to Ningthoujam and Nanda [46], the RVS procedure is a simple procedure for quick evaluation of large building stock, usually based on the walk down surveys on-site for each building to provide an indication about the buildings that need more advanced analysis. This method utilizes the scores given to building type (known as structural score or base score) and performance modifiers to decide the level of risk of building. The performance modifiers reflect the effect of building deficiencies (i.e., vulnerable parameters) on its response during ground shaking [47]. Therefore, from the RVS result (i.e., final score), one can prioritize the buildings. It also depicts that the score values assigned to each vulnerable parameter play a crucial role in deciding the risk (i.e., performance) of building. In the paper, some of the methods' strengths and weaknesses are discussed in the following paragraphs. A few more methods are addressed in the later sub-section and section, and a comparative study is presented.

The method for low-rise RC buildings, based on the priority index obtained by the addition of wall index and column index, was proposed by Hassan and Sozen [24]. As per this method, both the wall index and column index were obtained by normalizing the respective area with the total floor area. Therefore, the building's assessment is carried out based on two parameters only, i.e., total wall area and total column area. Similarly, the RVS method developed by Gulkan and Sozen [25], which also considers the orientation and cross-section sizes of columns and walls, added one more parameter in the assessment, that is, drift. As per this method, the columns and walls highly influence the drift on the ground floor. Though these two methods were practical and straightforward, other building parameters such as material and construction quality and effects of plan irregularity and vertical irregularity are ignored.

In Japan, the Japan Building Disaster Prevention Association (JBDPA) developed guidelines for seismic evaluation of existing reinforced concrete buildings in 1977. Later it was revised in 1990 and 2001 [26]. As per this procedure, the seismic index, a product of primary seismic index, irregularity index, and time index, should be calculated at each storey and in each principal direction of the building. The structure's primary seismic index is the building's primary seismic performance, assuming no complexity. The irregularity index evaluates complexity related to plan and section, whereas the time index evaluates the structural defects such as deflection, cracking, aging, etc. This evaluation is based on many parameters, and there is no clarity regarding the scoring system and ranking of buildings.

The New Zealand standard [31] recommended a two-stage evaluation process. Using the initial evaluation process (IEP), the existing building's structural performance is compared with the standards required for new buildings. It is expressed in terms of percentage new building standard (%NBS) [31]. As per the standards, if the %NBS is less than 33, the building is likely to be an earthquake-prone building (EPB) and requires a more detailed assessment. A %NBS greater than 67 means the building does not have an earthquake risk. However, though %NBS between 33 and 67 means no action required by the law, the building may undergo unacceptable damage, and further detailed evaluation may be recommended. The objective of this is to identify the EPB with an acceptable confidence level. Therefore, this assessment method requires a well-trained and well-experienced earthquake engineer to achieve the same.

In 2007, Sucuoglu et al. [32] proposed a simple seismic risk assessment procedure to identify buildings with high damage risk and need priority during risk mitigation activities. The procedure is suitable for medium-rise ordinary reinforced concrete (RC) buildings only. The parameters which influence damage significantly and which are easy for visual observations were selected. The effect of each parameter towards damage in a building is quantified using statistical analysis. The procedure adopted in this method has some similarities with other proposed evaluation procedures as well, such as FEMA-154 [21,22], Jain, et al., [35,36], and METU [28]. The RVS method developed by FEMA-154 [21,22] and Jain et al. [35,36] has been discussed later in this paper.

After critically reviewing the available RVS procedures, Wang and Goettel [33] proposed a new enhanced rapid visual screening (E-RVS) method. It was concluded from the review that it is difficult to interpret the logarithmic relation between the final RVS score and the probability of collapse. Also, the use of site-specific seismic hazard data in any RVS procedure would give more accurate results than seismicity regions. Therefore, the E-RVS method re-evaluated the score modifiers making it easy to evaluate the final score. In similar ways, Yadollahi et al. [40] also found that the RVS score is a little challenging to interpret when the value is determined from the logarithmic relation between the probability of collapse and the seismic vulnerability score. To overcome this difficulty, Yadollahi et al. [40] proposed a new scoring scheme that is non-logarithmic and linear. These proposed scoring schemes are based on the analytical hierarchy process (AHP). However, the method considered very few parameters and lacked clarity regarding the cut-off scores for ranking the buildings.

Likewise, various methods differ in expenditure, precision, and many other aspects [48]. Therefore, to contribute to this discussion, this paper presents the comparison and critical review of existing RVS methods. The RVS methods developed exclusively for Indian region (Arya 2003 [27]; Sinha and Goyal 2004 [29]; Jain et al. 2010 [35,36]; BMTPC (2012) [19,20]) are considered for this study. Along with this FEMA-154 (2015) [22], the RVS method widely used in the United States and many other countries is also considered. The background information on these selected methods is provided in the paper. Many other RVS methods are not directly included in the comparative study but are included as literature to illustrate particular features. To compare the selected RVS methods, a new scoring system is developed following Hill and Rossetto [49] and Alam et al. [17]. Finally, to highlight the utility of the RVS methods, three different case studies are performed. Nearly 100 sample buildings were surveyed in each of the three cities (Pithoragarh, Gangtok, and Agartala) of India, using all five RVS methods. The geo-static map of the study area has been shown along with the damage scales distribution of RVS methods.

2.1. Sinha and Goyal (2004)

In 1988, Federal Emergency Management Agency (FEMA) published the first edition of the FEMA-154 report that included a rapid visual survey procedure for identifying the buildings that might pose a severe risk of loss of life when a damaging earthquake occurs. Adopting a similar approach described in the 2002 version, Sinha and Goyal in 2004 developed an RVS method that suits the Indian conditions. The primary objective was to identify if a particular building requires further evaluation to assess its seismic vulnerability [29]. The method consists of two main factors: the *basic score* and *score modifiers*. The basic score is a generic score assigned to a building typology with no vulnerability present in it. Score modifier is a score given to those building vulnerability parameters which affect building performance during an earthquake. The advantage of using this method for assessment is that the method clearly defines the expected damage state of the building qualitatively, for example, slight damage, moderate damage, etc. But the technique lacks clarity in explaining the basic score values of each building typology, score modifier values for each vulnerable parameter, and cut-off values for each damage state.

2.2. Arya (2003)

This method aims to identify whether the building requires further evaluation or not [27]. According to Arya, when an earthquake of high intensity occurs, different building types experience different damage levels depending on their inherent characteristics [27]. Therefore, this method focuses on the seismic vulnerability based on the lateral load resisting system, the materials used, and the region's seismicity where the building is located. The vulnerable parameters considered are torsion irregularity, re-entrant corners, diaphragm discontinuity, and out-of-plane offset as a plan irregularity and mass irregularity and stiffness irregularity as a vertical irregularity. This RVS method is one of the very few methods in which no score values are assigned to any parameter. It recommends a detailed evaluation if any one of these parameters present in the building. The level of damage experienced by a building depends only on the type of a building, its lateral load resisting system, and the type of materials used. There are many shortcomings in this RVS form. Most importantly, this method is not calibrated on any actual building damage data from any Indian earthquake. As the document specifies the 'damageability' of buildings in different zones based on the construction materials alone, it underestimates or overestimates the building's strength.

2.3. Jain et al. (2010)

In 2010, Jain et al. [35,36] proposed a new method for assessing reinforced concrete (RC) buildings in India. This method aims to identify seismically vulnerable buildings and neighbourhoods, which is a necessary step for developing effective disaster mitigation programs for the community [35]. The method was developed based on systematic studies on damage data of Ahmedabad City after a massive 2001 Bhuj earthquake [35]. This damage data contained comprehensive information about buildings, such as the observed damage state of the building and vulnerability parameters present in the building. Once the observed parameters were noted, various variable selection techniques were used to identify statistically significant vulnerable parameter. Upon selecting the vulnerable parameters, the number of buildings or percentages of buildings suffering a different level of damages with the feature or parameters was computed, and regression analysis was performed using Eq. (1) [35].

$$EPS = A + C_0x_0 + C_1x_1 + C_2x_2 + C_4x_4 + C_5x_5 + C_7x_7 \quad (1)$$

Here, *EPS* represents the expected performance score of a building. x_i being the vulnerability parameter (x_0: presence basement; x_1: number of stories; x_2: maintenance; x_3: the presence of staircase symmetric with the plan; x_4: re-entrant corners; x_5: open storey; x_6: stub column; x_7: short column). C_i represents the score value of that vulnerability parameter, and constant *A* being the base score of the building corresponding to the seismic zone and number of storeys. The procedure gives score values fairly, based on statistical analysis.

The procedure (i.e., statistical selection techniques) used to select vulnerable parameter is the major shortcoming of this method. It was observed that all statistical techniques suggest all parameters except x_3, x_5, and x_6 parameters. None of the techniques do recommend the parameter x_6, therefore not included in the final form. These variable selection techniques used are not always reliable, and the example is an open storey parameter. RC building with no masonry walls present at the ground storey or any storey is said to have an open (soft) storey. The presence of this parameter can cause severe damage to the building during an earthquake. Only two statistical selection techniques suggest this vulnerable parameter (i.e., open storey). Similarly, if the staircase is not symmetric with the building's plan, it creates torsion in the building, causing severe damage. This parameter is also suggested by only one technique.

Another important aspect is the damage scenario. The method developed is based on the building damage data collected after the 2001 Bhuj earthquake. This data cannot be used for creating RVS for another region because of construction technology, material quality, soil profile, and many more changes from area to area. Therefore, building damage data from only one place cannot be generalized. To justify this, one can refer to the FEMA-155 (2002) [50] document, which quotes, "Risk to the modern unreinforced masonry buildings in the Central United States may be overestimated if California experience is the basis for the Basic Structural Hazard Score in this region."

Table 1
Major Vulnerability Parameters considered in different RVS methods.

	Vulnerability Parameter	Sinha and Goyal (2004)	Arya (2003)	Jain et al. (2010)	BMTPC (2012)	FEMA-154 (2015)
Siting Issue	Liquefaction	Y*	YN***	N	Y	N
	Building on a river terrace	N**	YN	N	Y	N
	Building on a hill slope	Y	YN	N	Y	Y
	Seismicity of Region	Y	Y	Y	Y	Y
Soil & Foundation	Type of soil	Y	YN	Y	Y	Y
	Foundation type	N	YN	N	Y	N
Architectural Features	Plan irregularity	Y	YN	-****	Y	Y
	Re-entrant corner	Y	–	Y	Y	Y
	Pounding effect	N	N	N	Y	Y
	Large projections	N	N	N	Y	N
	Soft storey	Y	–	Y	Y	Y
Structural Aspects	Type of structure	Y	Y	Y	Y	Y
	Frame action	N	N	N	Y	Y
	Type of roof	N	N	N	Y	N
	Short column	Y	N	Y	Y	Y
	Staircase connectivity	N	YN	N	Y	N
	Code compliance	Y	N	N	–	Y
Construction Details	Quality of materials	N	N	Y	Y	N
	Occupancy	YN	YN	Y	N	YN

*Y considered, **N not considered, ***YN considered but no score assigned, ****- not mentioned.

2.4. BMTPC (2012)

BMTPC (Building Materials and Technology Promotion Council) in 2012 documented a methodology for the seismic safety assessment of typical housing typologies in India. The method is a result of an intensive field survey and a detailed study of historical documents. It provides a *seismic safety index* and performance rating to a building with respect to an ideal building of the same typology. Moreover, it divides all vulnerability parameters into two categories, viz., *life-threatening parameters* and *economic loss inducing parameters*. Each economic loss inducing parameter has been assigned a score value or index values derived based on *Delphi-Method*. Delphi method includes the only experts where experts, based on the previous study and their experience, assigns score values to each parameter. As this method separates each factor into two sets, it becomes easy to determine the factors affecting life safety. But it has a few disadvantages over its use. First, the method is time-consuming and requires much more detailed information, which sometimes may not be possible to acquire. Another significant drawback is that this method has not been verified with any other RVS methods.

2.5. FEMA-154 (2015)

The RVS method prescribed by FEMA-154 was revised in the year 2002 and 2015. The report describes a rapid visual screening procedure for identifying those buildings that might pose a severe risk of loss of life and injury when a damaging earthquake occurs [21]. The method consists of two main factors: the *basic structural hazard score* and *score modifiers*. These scores use probability concepts based on the expected ground shaking levels, seismic design, and construction practices of the city or region [21]. Basic structural hazard (BSH) score is calculated using Eq. (2) [21].

$$BSH = -log_{10}[P(collapse\ given\ MCE)] \quad (2)$$

A similar equation is used to derive the SMs (Score Modifiers) with slight modification in the procedure. The term MCE represents the Maximum Considered Earthquake. The BSH Score excludes all the parameters that may or may not affect the building behaviour. This BSH Score is then modified for a building using score modifiers (SMs), depending on the number of vulnerable parameters present. The probability of collapse Eq. (2) is derived by determining the likelihood of being in the complete damage state, using the spectral displacement response value from the intersection point between the capacity-demand curve and the fragility curve for the entire damage state for the given building type. The same equation Eq. (2) was used to derive the SMs and small change in procedure. The procedure consists of initially calculating the scores for building considering each vulnerable parameter present individually using Eq. (2) and finally differencing those scores from the BSH Score of the same building. The final score of any building is calculated using Eq. (3) [21].

$$S = BSH\ Score \pm SMs \quad (3)$$

The FEMA-154 (2002) RVS method has few SM values based on practicing engineers' judgment even though it clearly describes the procedure. The 2002 version also clearly ignored the important building parameters such as construction and material quality and secondary effects of large overhangs and pounding effects.

The latest version, FEMA-154 (2015), has two levels of forms L1 and L2. For the current study, only level 1 form, i.e., the L1 form, is considered. According to FEMA-154 (2015), the building's level 2 assessment is optional and needs to be performed by civil or structural engineering professional who has enough background in seismic evaluation and design. Though the definition of the score as described in Eq. (2) is not modified in the latest revision, the revisions to the RVS scoring were done with modifications in (a) ground motions, (b) seismicity of the region. Unlike the previous versions, in which score for the plan, and vertical irregularity was based on engineering judgments, in the latest revision, the same score values were developed using the 'OSHPD HAZUS methodology.' The latest version has also considered the construction quality, material quality, large overhangs, and pounding effects but in second level (L2) assessment.

3. Comparative study

Safety assessment of existing RC buildings and their current state is the main focus of this study; hence the application and use of selected five RVS methods are studied. A comparison of vulnerable parameters used to assess buildings is done following Ercan [14] and presented in Table 1. All the structural elements related to vulnerability parameters are re-grouped under five broad categories: site issues, soil & foundation, architectural features, structural aspects, and construction details (Table 1).

Except for the code compliance parameter, wide ranges of vulnerability parameters are considered in BMTPC (2012) method. The Arya (2003) method takes into consideration only the most critical vulnerability parameters. However, these parameters were not assigned any score or value. The parameters considered in Sinha and Goyal (2004) method and FEMA-154 (2015) method are fair enough whereas, the number of parameters considered in the Jain et al. (2010) method is

Table 2
Comparison of Damageability grades considered in different RVS methods.

RVS Methods	Damage Scales				
Sinha and Goyal (2004)	No Damage	Slight	Moderate	Severe	Destruction
Arya (2003)	No Damage	Slight	Moderate	Severe	Destruction
Jain et al. (2010)	No Damage	Slight	Moderate	Severe	
BMTPC (2012)	ELISEF*				LTSEF**
FEMA-154(2015)	No Collapse				Collapse

* ELISEF: Economic Loss Inducing Structural Element-related Factors
** LTSEF: Life-Threatening Structural Element-related Factors

Table 3
Characteristics of rapid visual survey methods (after Alam et al. [17] and Hill and Rossetto [49]).

Characteristics	Sub-category	Definition
1. General description	1.1 experimental values	Does experimental values from laboratory testing or in-situ non-destructive test (NDT) values required
	1.2 site-specific	Are the parameters site-specific
2. Physical parameter	2.1 global parameter	Does parameters causing global damage to the building considered
	2.2 local parameter	Does parameters causing local damage to the building considered
	2.3 scope	Does different range/variations in the vulnerability parameters considered separately
	2.4 impact of NSE*	Does impact of non-structural element is considered in assessment
3. Damage description	3.1 damage grade	Does all 5 damages grades describe
	3.2 calibration	Are the expected damage states calibrated with experiment, analytical result or field survey of damaged buildings

relatively less.

In any rapid assessment methods, damage grades are used to label the building's performance limit state. A suitable and straightforward differentiation between each damage grade makes the rapid assessment of buildings easier. Moreover, each method's scoring system varies between specific ranges of numerical values, making it difficult to compare the results of any two different RVS methods. Therefore, comparing the damageability grades of the RVS methods is much appropriate. Along with the ranking of buildings in building stock, the selected RVS methods have also proposed an expected damage level of the building, which is a function of the final RVS score. The damage levels considered in all five RVS methods are shown in Table 2.

Each RVS method has different input factors as well as damageability grades. As Sinha and Goyal (2004) and Arya's (2003) methods follow damage levels as per the European macro-seismic scale, both methods have five damage grades from no damage state to destruction, i.e., collapse state. In Jain et al. (2010) method, the damageability grades are classified into four levels (i.e., no damage, slight damage, moderate damage, and severe damage) whereas, BMTPC (2012) method has only two damage levels, which are related to life safety and economic loss. According to BMTPC (2012) method, the building should be declared as unsafe if any one life-threatening vulnerability parameter is present; otherwise, structural performance rating should be carried out. On the other hand, the FEMA-154 (2015) method aims to identify those buildings with a severe risk of losing life due to its collapse. Therefore, though it is not explicitly mentioned as damage grades, the FEMA-154 (2015) method indirectly distinguishes buildings into two classes, i.e., collapse and no collapse. The method suggests a detailed investigation of buildings falling in the category of collapse grade.

Table 4
Definition of "significant," "moderate," "minimum," and "unsatisfactory" in quantifying categories (after Alam et al. [17] and Hill and Ressetto [49]).

Condition	Definition	Score
Unsatisfactory	Not a single observation available	0
Minimum	Guidelines meet the minimum requirement (1 or 2) for the criteria	1
Moderate	Very few (3 to 4) observations are available for any criteria	2
Significant	Enough (more than 4) observations are available for any criteria	3

Table 5
Individual scores of RVS methods for each sub-criterion.

Sub-Criteria	Sinha & Goyal (2004)	Arya (2003)	Jain et al. (2010)	BMTPC (2012)	FEMA-154 (2015)
1.1 experimental values	0	0	0	0	0
1.2 site – specific	3	3	3	3	3
2.1 global parameter	2	2	2	3	2
2.2 local parameter	2	1	3	3	3
2.3 scope	1	1	2	3	3
2.4 impact of NSE*	0	0	0	3	0
3.1 damage grade	3	3	2	1	1
3.2 calibration	0	0	3	3	0
Summation	11	10	15	19	12

* NSE: Non-Structural Element

3.1. *Scoring system to compare rapid visual screening methods suggested by Hill and Rossetto [49]*

A scoring system is developed to compare the rapid visual screening methods based on their characteristics following Alam et al. [17]. This scoring system is described in the following Tables 3–5. Table 3 contains three main characteristics of any rapid assessment methods based on which the comparison is performed. It also shows the sub-category of each characteristic and its definition. Table 4 contains the definitions for quantifying the sub-categories. Table 5 shows the category wise scoring of each RVS method and the total score of each method obtained by summing up each criterion's scores. The score obtained in each of the three sections is given equal weighting in calculating the total score of the RVS method [49].

The scoring system shown in Table 3 has three main criteria and eight sub-criteria. The primary purpose of developing this scoring system is to show variation in RVS methods based on the vulnerability parameter alone. The first criteria comprise the general description of inputs required for assessment, such as whether the inputs are site-specific or whether experimental values are needed. This will help to understand the variety of inputs required for each RVS method. The second criterion is the vulnerability parameter. It includes those parameters that can cause global and local damage to the building and non-structural elements, causing damage to the building. An important sub-category in this criterion is the scope of vulnerability parameters. Some methods consider two or more parameters under a similar heading. For example, FEMA-154 (2015), Sinha and Goyal (2004), and Arya's (2003) method considers mass irregularity and open ground storey as vertical irregularity with a single score value. But practically, the effect of both parameters is different when present in a building. Therefore, it is necessary to consider both parameters separately, even though both parameters are of vertical irregularity type. The third

Table 6
Weighting scenarios (after Hill and Rossetto [49] and Alam et al. [17]).

Weighting scenarios for scoring system	Criteria A (General description)	Criteria B (Physical parameter)	Criteria C (Damage description)	Description
I	33.33%	33.33%	33.33%	Default
II	50%	25%	25%	To highlight scales more suited for experimental and site-specific measurements
III	25%	50%	25%	To highlight scales more suited for safety analysis based on physical parameters
IV	25%	25%	50%	To highlight scales more suited for decision makers based on damage description

criterion deals with the damage description that includes the range of damage grades considered and the calibration of RVS results.

The main aim of the scoring system is to qualitatively indicate the rapid assessment methods' performance or reliability [17]. To provide a clear demonstration of each rapid method's performance, an affirmative statement (where sufficient, i.e., more than four observations are available) is given as three points. If, for any criteria, the method's performance is moderate (where very few, i.e., 3 to 4 observations are available), then the score is two points. Similarly, suppose the performance is minimum (i.e., only 1 or 2 observations available). In that case, the score is one point, and for unsatisfactory performance (i.e., not a single observation available), the score is zero points. The total score of each method is calculated by adding all scores of respective sub-criteria.

The individual scores of all five RVS methods for all sub-criteria are summarized in Table 5. To better understand the scoring system, let's take an example of sub-criteria 2.4 (i.e., NSE's impact). Jain et al. (2010) method have no vulnerable parameter related to NSE's impact, whereas one can find more than four vulnerable parameters related to it in BMTPC (2012) method. Therefore, for sub-category 2.4, the Jain et al. (2010) method's score is 0, and BMTPC (2012) method's score is 3. Table 5 shows that BMTPC (2012) method has the highest score than the other four methods. It has enough global as well as local vulnerability parameters. It also includes different types of irregularities with proper index values assigned to each type. Further, it is the only method considering the impact of non-structural elements during the assessment.

Arya's (2003) method has a significantly less number of local parameters with less scope, due to which the method has the least score among all. Sinha and Goyal (2004) and Arya (2003) RVS method has different types of irregularities under a similar title (for example, all types of vertical irregularities are grouped and titled as vertical irregularity only). Whereas, BMTPC (2012) and FEMA-154 (2015) method include sub-categories of vertical irregularities and assigns index values to each.

3.2. Multi-criteria-based decision analysis for ranking rapid visual screening methods

It is necessary to obtain several weighing and tabulated values during the definition of simplified methods for vulnerability assessment [51]. Typically, many researchers apply time-consuming trial and error procedures [52], which can compromise the method's effectiveness. To overcome this, some authors use the Analytical Hierarchy Process (AHP) [53], which is a multi-criteria decision making (MCDM) based procedure. The AHP results particularly useful in decomposing and reorganizing any indirect risk assessment methods in a well-defined hierarchy of involved parameters [51]. AHP stresses the significance of decision-makers' wise judgments and consistency in comparing the alternatives in the decision-making process [17,53].

Three criteria are considered for comparing different RVS methods using MCDM and denoted as A, B, and C, respectively. These three criteria are nothing but the characteristics of any RVS methods, as described in Table 3. Different researchers or specialists may use different weights on scoring criteria according to their specific needs. Therefore, a sensitivity analysis has been performed to check the influence of criteria weighting on the final score. Criteria are weighted according to four scenarios (I-IV) shown in Table 6. Further, using the hierarchy process, a pair-wise comparison is carried out, and finally, using weights (example of scoring is shown in Table 7), all RVS methods are ranked (Table 8).

As the equal weighting for each criterion is adopted in scenario-I (shown in Table 6), it gives an overall view of each RVS method's performance. Table 7 shows an example of a scoring system of the BMTPC (2012) method for scenario-I. The final score of each sub-criterion is obtained by multiplying the weight assigned and the corresponding score of the RVS method. The weights to each sub-criterion are given in such a way that it satisfies the equal weighting criteria. For example, the summation of sub-criteria 1.1 and 1.2 is two, so the summation of sub-criteria is 2.1, 2.2, 2.3, and 2.4.

A significant change in each RVS method's final ranking can be observed by making small changes in the weights. Table 8 shows that the final ranking of BMTPC (2012) and Jain et al. (2010) method remains unchanged from scenario I to IV. A little variation in the FEMA-154 (2015) and Sinha and Goyal (2004) method for scenario III, whereas a significant variation in the ranking of Arya's (2003) method can be observed. It is evident from Table 8 that BMTPC (2012) and Jain et al. (2010) are the best alternatives, whereas Arya (2003) is the unsuitable

Table 7
Example of a scoring system for BMTPC (2012) method.

Sub-Criteria	BMTPC Method Score	Weighting scenario I	Final Score
1.1	0	1	0
1.2	3	1	3
2.1	3	0.5	1.5
2.2	3	0.5	1.5
2.3	3	0.5	1.5
2.4	3	0.5	1.5
3.1	1	1	1
3.2	3	1	3
Total			*13*

Table 8
Result of Sensitivity analysis.

Rapid visual screening methods	Ranks			
	Scenario I	Scenario II	Scenario III	Scenario IV
Sinha and Goyal (2004)	3	3	4	3
Arya (2003)	4	4	5	3
Jain et al. (2010)	2	2	2	2
BMTPC (2012)	1	1	1	1
FEMA-154 (2015)	4	4	3	4

Table 9
Information on Cities visited.

City Name	State	Latitude	Longitude	Zone	Terrain
Pithoragarh	Uttarakhand	29.58^0 N	80.22^0 E	V	Hilly
Gangtok	Sikkim	27.33^0 N	88.61^0 E	IV	Hilly
Agartala	Tripura	23.50^0 N	91.16^0 E	V	Plain

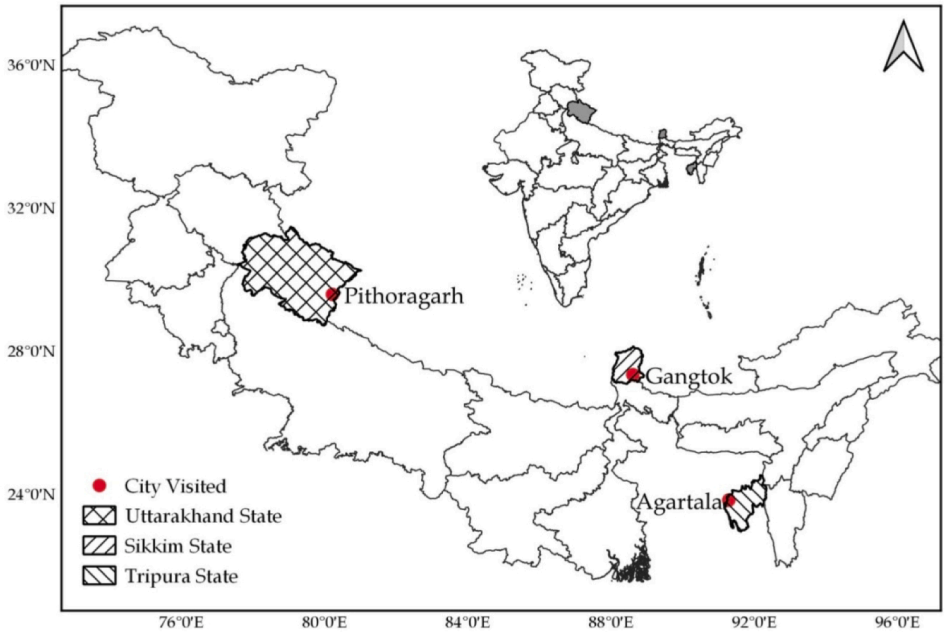

Fig. 1. The geographical location of three cities visited for the case study.

method.

4. Case study

A case study has been performed to investigate the similarity of results of different RVS methods. This study includes a survey and collection of 100 samples of RC buildings in each of the three cities, mainly Pithoragarh, Gangtok, and Agartala. Table 9 shows the geographical data of these three cities.

Pithoragarh city is situated close to the India-Nepal border and is surrounded by Himalayan mountain ranges. A significant part of the town is under a complex landscape, with nearly 55 to 60% of the land having steep to extremely steep slopes. Gangtok city is the capital city of India's one of the smallest and extremely mountainous state, Sikkim. Like Pithoragarh, Gangtok city is also located in a hilly area, but comparatively, its topography has sharply defined and extremely steep watersheds. The town falls near the convergent boundary of Indian and Eurasian tectonic plates and is subjected to frequent earthquakes. More than 90% of the total buildings in the city are constructed on steep slopes. Agartala city is the capital of Tripura state. It is the second-largest and one of the important towns in northeast India. The city is located at the foothills of the Himalayas, on the banks of Haora River, and has plain terrain. The geographical location of all three cities is shown in Fig. 1.

4.1. Seismicity of study area

The Continuous convergence between India and Eurasia has given rise to the spectacular Himalayas and a 2500-km-long seismic belt,

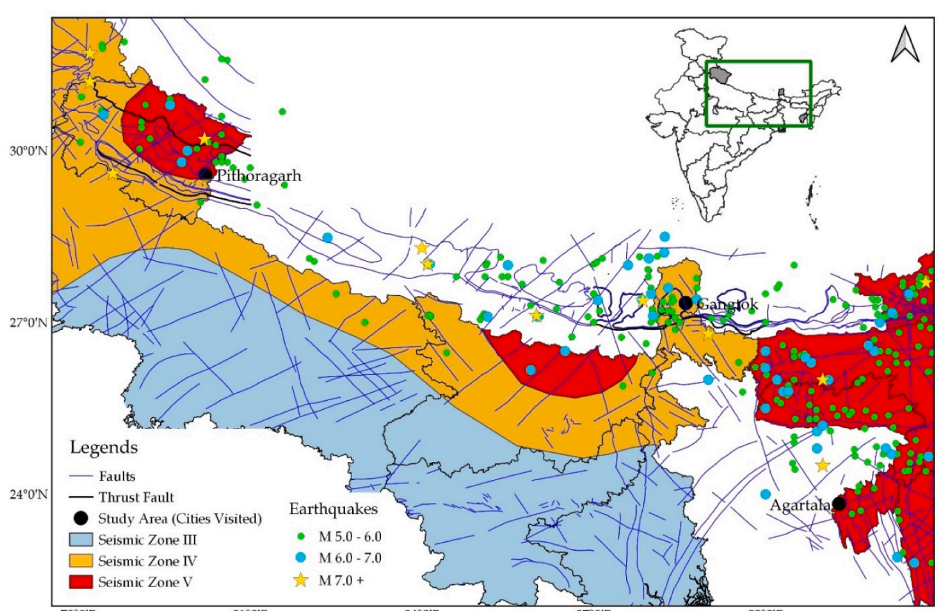

Fig. 2. Seismotectonic and earthquake map of Uttarakhand, Sikkim, Tripura, and adjoining area.

Table 10
Past earthquake records near Pithoragarh, Agartala, and Gangtok city.

City	Date	Magnitude
Pithoragarh	June 27, 1966	6.3
	July 29, 1980	6.5
	February 19, 1984	5.0
	October 19, 1991	6.8
	January 05, 1997	5.6
	March 28, 1999	6.5
	June 22, 2010	5.2
	April 04, 2011	5.3
	April 25, 2015	7.8
	December 01, 2016	5.2
Agartala	June 21, 1963	5.7
	October 30, 1980	5.0
	May 21, 1984	5.3
	February 06, 1988	5.9
	April 13, 1989	5.5
	November 19, 1996	5.4
	May 08, 1998	6.0
	August 12, 2006	5.0
	September 10, 2010	5.1
	January 03, 2016	6.7
Gangtok	January 12, 1965	5.9
	November 19, 1980	6.1
	August 20, 1988	6.9
	September 25, 1996	5.0
	March 25, 2003	5.5
	February 14, 2006	5.3
	September 18, 2011	6.9
	October 03, 2013	5.2
	April 25, 2015	7.8
	May 12, 2015	7.3

Source: www.asc.india.org

causing large and great earthquakes from Kashmir Himalaya in the west to Arunachal Himalaya in the east [54]. Among the three selected cities, Pithoragarh (state of Uttarakhand) and Gangtok (state of Sikkim), both cities are located on this seismic belt.

The seismicity of the Himalayas largely governs the seismicity of Uttarakhand and Sikkim states. The seismicity of the plate boundary region is mainly influenced by different prominent Himalayan tectonic thrusts, namely main boundary thrust (MBT), main central thrust (MCT), and main frontal thrust (MFT) [55]. Both Uttarakhand and Sikkim states possess a very significant segment of MBT and MCT. Along with these important thrusts and faults, a large number of smaller thrusts, faults, and lineaments are also present in and around Uttarakhand [55].

Seismically, northeast India, where Agartala city (state of Tripura) is located, is one of the world's most active regions. The seismotectonic of northeast India has been summarised as the south directed over-thrusting from the north due to collision tectonics at the Himalayan arc, and northwest directed over-thrusting from the southeast due to subduction tectonics at the Burmese [56]. Therefore, in this region, earthquakes of small to moderate magnitude occur quite often [57].

4.2. Preparation of seismotectonic and earthquake map

All the important tectonic features, such as thrust faults and local faults in and around the study area, were collected from different available sources. Geological Survey of India (GSI) has published the seismotectonic atlas of India (SEISAT 2000) [58] that contains 43 sheets. These sheets cover the entire India region and seismically active regions of neighbouring countries close to Indian borders.

For simplicity, the seismotectonic and earthquake maps are superimposed into a single map (Fig. 2). The details of past earthquakes (≥5 M) for all the cities were also collected from different sources such as the Indian Metrological Department (IMD), U. S. Geological Survey (USGS), and International Seismological Centre (ISC). Some of the earthquakes are listed in Table 10. The georeferenced and digitized seismotectonic atlas and earthquake maps of nearby regions of the study area were superimposed using QGiS software (Fig. 2).

Table 11
Sample surveyed buildings and their deficiencies.

Building Photo	Building Survey
Fig. 3	***Sinha and Goyal (2004)*** 2.6 (Base Score) + 0.2 (Mid Rise) – 1.0 (Vertical Irregularity) – 0.5 (Plan Irregularity) + 0.2 (Code Detailing) – 0.4 (Soil Type II) = ***1.1*** ***Jain et al., (2010)*** 55 (Basic Performance Score) + 0 (No Basement) + 10 (Number Storey > 5) – 0 (Good Maintenance) – 0 (No Re-Entrant Corners) – 10 (Open Storey) + 0 (No Non-residential Use) – 0 (No Short Columns) = ***55*** ***BMTPC (2012)*** 0 – 100 (Building has Life Threatening Factor i.e., Open ground Storey) = – ***100*** ***FEMA-154 (2015)*** 1.2 (Basic Structural Hazard Score – 0.7 (Severe Vertical Irregularity) – 0.0 (Moderate Vertical Irregularity) – 0.5 (Plan Irregularity) – 0.0 (Post Benchmark Building) – 0.0 (Soil Type E) = ***0.0 → 0.3***
Fig. 4	***Sinha and Goyal (2004)*** 2.6 (Base Score) + 0.2 (Mid Rise) – 1.0 (Vertical Irregularity) – 0.5 (Plan Irregularity) + 0.2 (Code Detailing) – 0.4 (Soil Type II) = ***1.1*** ***Jain et al., (2010)*** 65 (Basic Performance Score) + 0 (No Basement) + 10 (Number Storey > 5) – 0 (Good Maintenance) – 0 (No Re-Entrant Corners) – 10 (Open Storey) + 5 (Non-residential Use) – 0 (No Short Columns) = ***80*** ***BMTPC (2012)*** 0 – 100 (Building has Life Threatening Factors i.e., Building on Hill Slope/Building located close to adjacent unsafe building) = – ***100*** ***FEMA-154 (2015)*** 1.4 (Basic Structural Hazard Score – 0.8 (Severe Vertical Irregularity) – 0.5 (Moderate Vertical Irregularity) – 0.6 (Plan Irregularity) – 0.0 (Post Benchmark Building) – 0.0 (Soil Type E) = – ***0.5 → 0.3***
Fig. 5	***Sinha and Goyal (2004)*** 2.5 (Base Score) + 0.4 (Mid Rise) – 1.5 (Vertical Irregularity) – 0.0 (Plan Irregularity) + 0.2 (Code Detailing) – 0.4 (Soil Type II) = ***1.2*** ***Jain et al., (2010)*** 65 (Basic Performance Score) + 0 (No Basement) + 0 (Number Storey > 5) – 0 (Good Maintenance) – 0 (No Re-Entrant Corners) – 10 (Open Storey) + 5 (Non-residential Use) – 0 (No Short Columns) = ***70*** ***BMTPC (2012)*** 0 – 100 (Building has Life Threatening Factors i.e., Building on Hill Slope/Building located close to adjacent unsafe building) = – ***100*** ***FEMA-154 (2015)*** 1.7 (Basic Structural Hazard Score – 0.0 (Severe Vertical Irregularity) – 0.6 (Moderate Vertical Irregularity) – 0.0 (Plan Irregularity) + 1.9 (Post Benchmark Building) – 0.0 (Soil Type E) = ***3.0***

4.3. Comparison of RVS results

A rapid visual survey of RC buildings was carried out in all three cities using five RVS methods. It was observed during the field visit that construction techniques/styles are different in all three cities. Their respective culture, climate, and topography can be the reasons for this. While using the FEMA-154 (2015) RVS method, the seismic zone factor close to the Indian seismic zone factor is selected for respective cities (as per Seismic Zone Map of India) the rapid survey was performed. The methods consider the necessary seismic hazard level of each building. While conducting a rapid survey in three cities, forms of Sinha and Goyal (2004), Arya (2003), and FEMA-154 (2015) were selected as per the seismicity of each city as well as appropriate base score values were chosen for Jain et al. (2010) method.

Comparing only the final numerical score (quantitative result) of any two RVS methods does not conclude the study. Instead, one can compare the damage grades (qualitative result) of any two RVS methods. An

Fig. 3. The sample surveyed building in Agartala.

Fig. 4. The sample surveyed building in Gangtok.

Fig. 5. The sample surveyed building in Gangtok.

important point to mention here is that the effect of any vulnerability parameter on the performance of the building should be the same irrespective of the score value assigned in each RVS method. But during the field visit, it was observed that for many buildings, the qualitative results of RVS methods were not identical. Table 11 shows a few samples of surveyed buildings in Agartala (Fig. 3) and Gangtok (Fig. 4, Fig. 5) and their respective deficiencies. The results of the rapid visual survey for the same buildings are shown in Table 12.

For the building in Agartala shown in Fig. 3, when surveyed using Sinha and Goyal (2004) method and Jain et al. (2010) method, its final score is 1.1 and 55, respectively. The corresponding damage grade is the same for both, i.e., *moderate*. In the same building, when surveyed using Arya (2003) method, its damage grade is *slight,* and when surveyed using BMTPC (2012) and FEMA-154 (2015) method, its damage grade is *collapse*. The significant parameters affecting the performance of the building are the *soft storey* and *pounding effect*. But as the score weightage assigned to these parameters in each method is different, there is variation in results. The building in Gangtok shown in Fig. 4 is very close to the adjacent building and constructed on the hill slope. Due to this, there

Table 12
Comparison of RVS scores and corresponding Damage grades.

Building	Sinha and Goyal (2004)	Arya (2003)	Jain et al. (2010)	BMTPC (2012)	FEMA-154 (2015)
1	1.1 Moderate	– Slight	55 Moderate	−100 LTSEF*	0.3 Collapse
2	1.1 Moderate	– No	80 No	−100 LTSEF	0.4 Collapse
3	1.2 Moderate	– No	70 Slight	−100 LTSEF	3.4 No Collapse

is a high risk of *pounding effect*. The building also has vertical irregularity. The score of this building (Fig. 4), according to Sinha and Goyal (2004) method, is 1.1, which corresponds to moderate damage. According to Jain et al.'s (2010) method, the score is 80 with no damage, which contradicts the results of BMTPC (2012) and FEMA-154 (2015) method. Similar kinds of varying RVS results were observed in the other building, i.e., Fig. 5, and many other buildings in all three cities.

The final output of these methods, which is the expected damageability grade of the building, is determined for all 100 buildings from each city and compared. Figs. 6, 7, and 9 show the expected damageability grade of buildings in Pithoragarh, Gangtok, and Agartala city, respectively, as per all five methods. During the field survey, the coordinates of buildings only in Gangtok and Agartala city were noted additionally.

Therefore, as a continuation of Figs. 7 and 9 of Gangtok and Agartala city, respectively, Figs. 8 and 10 show the exact location of surveyed buildings in the two cities and the damage scale distribution of different RVS methods. In all three cities, the survey was conducted at various locations covering older parts of the city, newly developed residential colonies, government buildings, commercial places, and market areas.

In Pithoragarh city (Fig. 6), according to Sinha and Goyal (2004) method, nearly 60 buildings are expected to have moderate damage. In contrast, Jain et al.'s (2010) method shows almost 90 buildings with moderate damage and 37 buildings per Arya's (2003) method. Similarly, 40 buildings according to Sinha and Goyal (2004) method and nearly 48 buildings according to BMTPC (2012) method are expected to have slight damage, which is quite comparable, but according to Arya (2003) method, 21 buildings and according to Jain et al. (2010) method, only two buildings are expected to have slight damage which is a huge difference.

Adding to this, Jain et al.'s (2010) method and Arya's (2003) method shows the buildings with severe damage with a huge difference. The results of the FEMA-154 (2015) method and BMTPC (2012) method also have a massive variation in their result. According to the FEMA-154 (2015) method, 98 buildings are expected to have destruction, and according to BMTPC (2012) method, 52 buildings are expected to have destruction.

Fig. 7 shows the damageability grade comparison of a sample of 100 surveyed buildings in Gangtok city. It shows a considerable variation in the results of all five methods. In Gangtok city, according to Sinha and Goyal (2004) method, only one building is expected to have no damage, whereas according to Jain et al. (2010) method, 14 buildings and as per Arya (2003) method, almost 45 buildings are expected to have no damage. Similarly, as per Sinha and Goyal's (2004) method, 88 buildings are expected to have moderate damage, whereas according to Jain et al. (2010) method, 21 buildings and according to Arya (2003) method, 20 buildings are expected to have moderate damage. Here, for buildings with moderate damage, the results of the Jain et al. (2010) method and Arya (2003) method are almost similar, but it has a huge difference from the result of Sinha and Goyal (2004) method. Amongst these methods, Jain et al.'s (2010) method shows only one building with an expected damage grade as severe. According to Jain et al. (2010) method, 64 buildings, and according to Arya's (2003) method, 35 buildings are expected to have a slight damage. For this city, the results

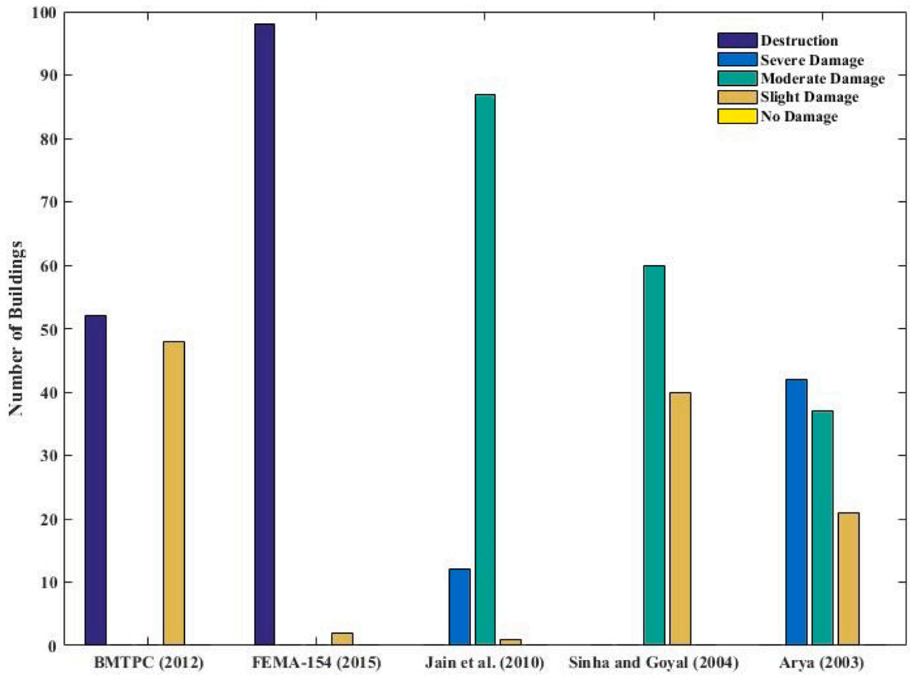

Fig. 6. Comparison of RVS results for sample 100 surveyed RC buildings in Pithoragarh city.

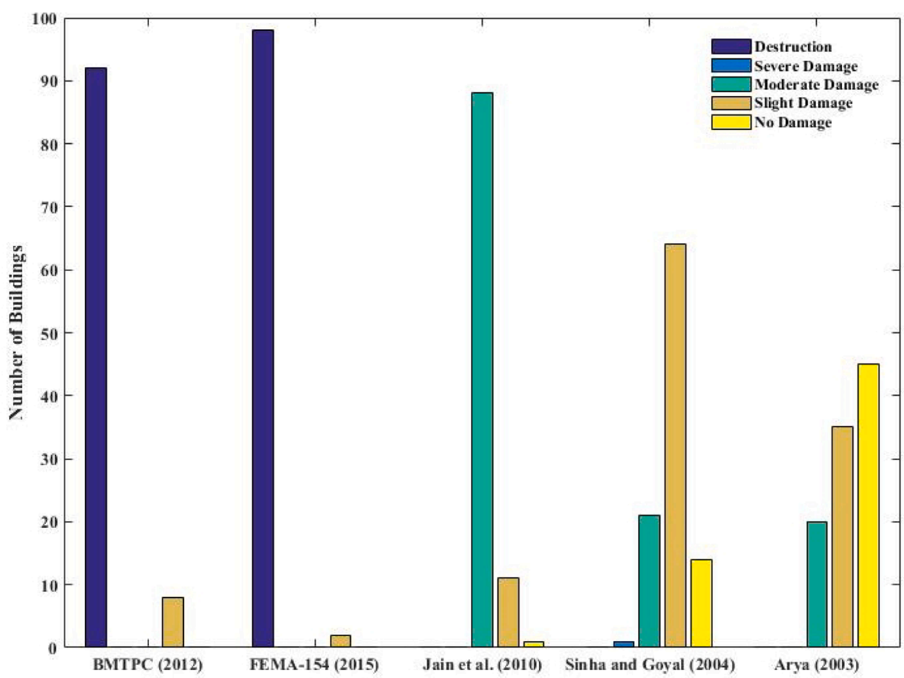

Fig. 7. Comparison of RVS results for sample 100 surveyed RC buildings in Gangtok city.

of FEMA-154 (2015) and the BMTPC (2012) method are quite comparable with significantly less difference.

On the other hand, when the results of all five RVS methods are compared for Agartala city, as shown in Fig. 9, there are substantial differences in each method. According to Sinha and Goyal (2004) method and Arya's (2003) method, nearly 45 buildings are expected to have a slight damage. Results of the Sinha and Goyal (2004) method show that 54 buildings are expected to have moderate damage, whereas Jain et al.'s (2010) method and Arya's (2003) method show 28 buildings with moderate damage. Among all 100 buildings surveyed in this city, only Jain et al. (2010) method and Arya's (2003) method show that nine buildings and 23 buildings, respectively, are expected to have severe damage. In contrast, the result of FEMA-154 (2015) and BMTPC (2012) method shows 96 and 39 buildings expected to have a destruction state, respectively.

Apart from comparing the damageability grades and characteristics, the important aspect that needs attention is the weightage assigned to each vulnerability parameter. Approximate estimation of the expected performance of a building or the expected damage level depends not only on parameters considered but also on the weightage assigned to

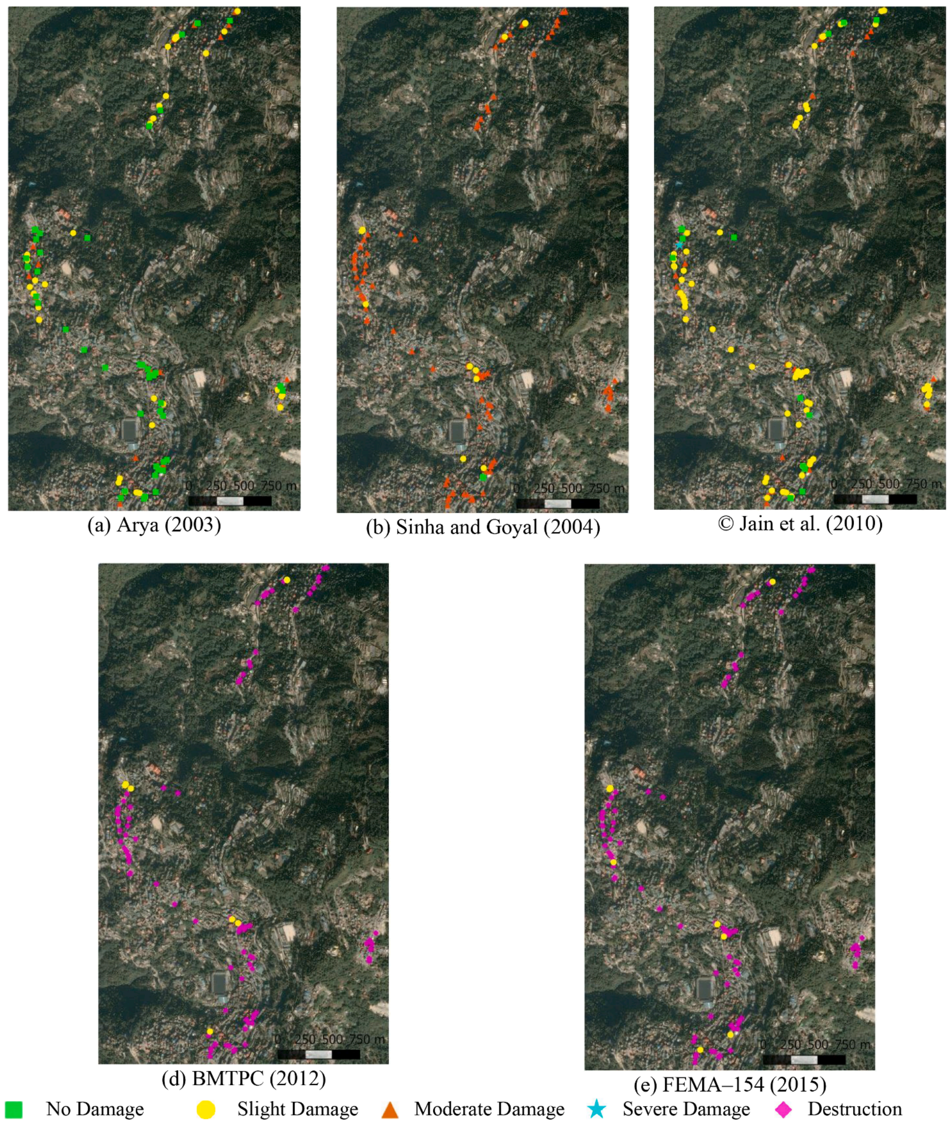

Fig. 8. Damage scale distribution of surveyed buildings with different RVS methods in Gangtok city.

each parameter. As the scores given to the building deficiencies can be normalized to determine their relative significance [15], the weightage assigned to each vulnerability parameter in each RVS method is determined and, for simplicity, re-grouped into five sub-categories as presented in Table 13. Note that Table 13 is the relative weightage value among five sub-categories; therefore, their summation is 100. The weightage values are determined only for reinforced concrete with unreinforced masonry building typology for higher seismicity.

From Table 13, it is evident that all the methods except Arya's (2003) method have given the highest weightage to architectural features compared to other factors. The relative weightage to the same factor in Sinha and Goyal (2004), BMTPC (2012), and FEMA-154 (2015) methods are comparable, i.e., 56%, 58%, and 61%, respectively. The relative weightage of soil and foundation factor and structural aspect factor in Sinha and Goyal (2004) and FEMA-154 (2015) method do not differ much. Similarly, the relative weightage of the structural aspect factor in Jain et al. (2010) and BMTPC (2012) method is comparable, i.e., 17% and 20%, respectively. Amongst all five methods, only BMTPC (2012) method has vulnerability parameters of all sub-categories. According to Arya's (2003) procedure, the building's damage grade depends only on the primary structural framing system; therefore, it has a relative weightage of 100% assigned to structural aspects only.

Comparison of relative weightage of soil & foundation and structural aspect factors for four methods, i.e., Sinha and Goyal (2004), Jain et al. (2010), BMTPC (2012), and FEMA-154 (2015) shows a vast difference in the values. BMTPC (2012) method has assigned 5% weightage to soil and foundation; in contrast to this, Sinha and Goyal (2004) have a weightage of 38%. A similar contradiction can be observed in structural aspects where 4% relative weightage is assigned by FEMA-154 (2015), and 20% relative weightage is assigned by BMTPC (2012).

Table 13 depicts that buildings' performance varies from one method to another method in the presence of any vulnerability parameters. This difference in parameter weightage has resulted in varying results (Figs. 6–10). It also makes the assessment of building performance challenging to understand.

5. Conclusion

For mitigation of damage before any future earthquake events, it is necessary to identify deficient buildings from large building stocks in any city or town. This can be achieved only with rapid visual survey (RVS) methods followed by benchmarking of scores with a detailed assessment. This paper presents a comparative study and a critical review of the existing rapid visual screening methods. Five different RVS methods exclusively used for the assessment of RC buildings were selected in this study.

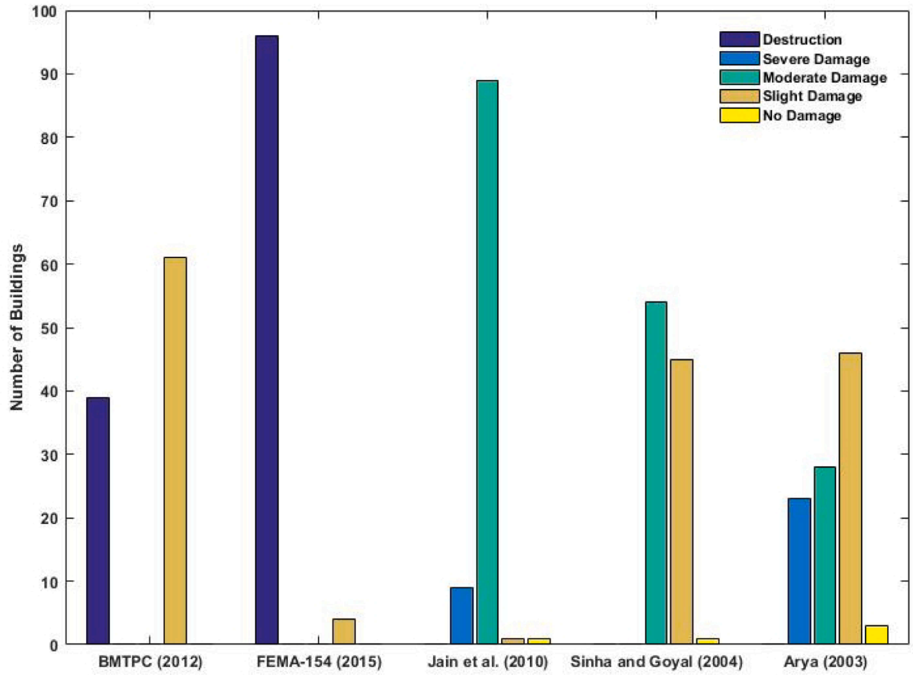

Fig. 9. Comparison of RVS results for sample 100 surveyed RC buildings in Agartala city.

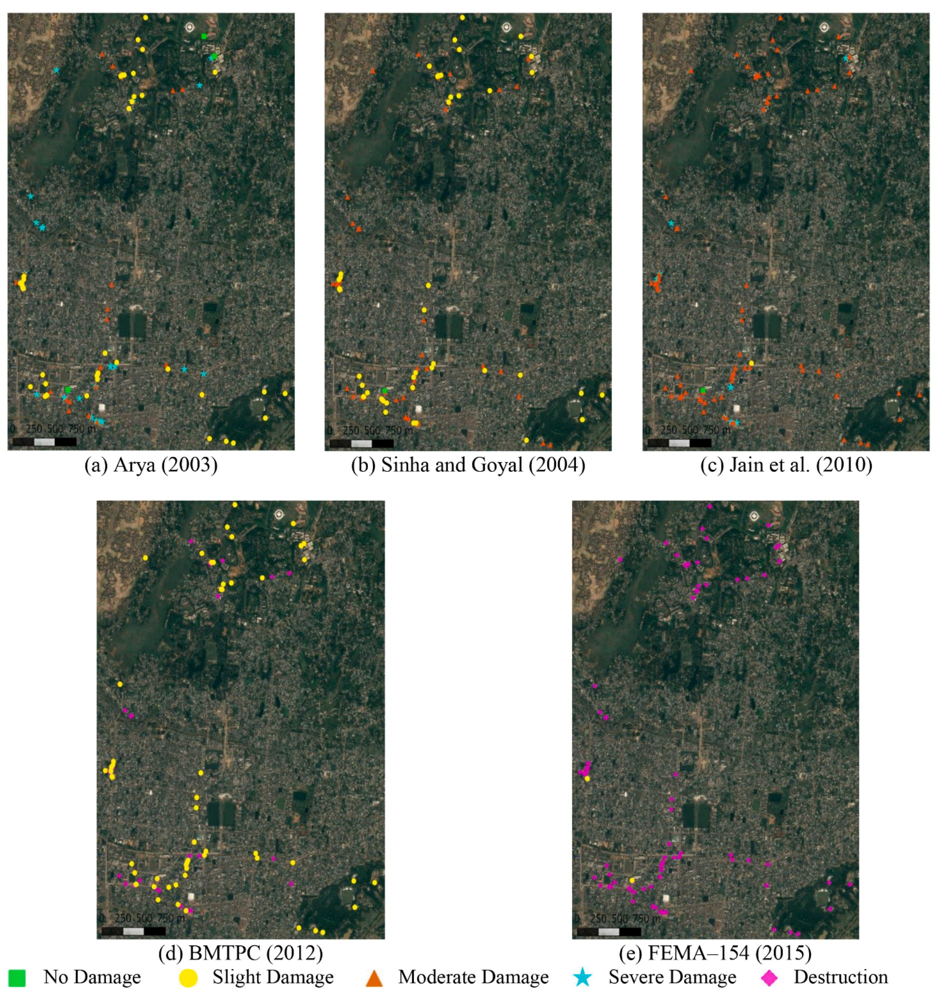

Fig. 10. Damage scale distribution of surveyed buildings with different RVS methods in Agartala city.

Table 13
Comparison of weightage (percentage) assigned to each factor.

Structure Related Factors	Sinha and Goyal (2004)	Arya (2003)	Jain et al. (2010)	BMTPC (2012)	FEMA-154 (2015)
Site Issues	00	00	00	05	00
Soil & Foundation	38	00	17	05	35
Architectural Features	56	00	44	50	61
Structural Aspects	06	100	17	20	04
Construction Details	00	00	22	20	00

A comparative study was performed in various ways. The first comparison is performed based on vulnerable parameters considered in all five RVS methods. As each RVS method adopts a different scoring system for assessing building performance, it is complicated to directly compare only the final score value of any two methods. Instead, comparing the qualitative results, i.e., damage grades, is more appropriate. Therefore, the second comparison is made based on damageability grades proposed by each RVS method.

After a simple and straight forward comparison, the RVS methods are further compared using the arbitrary and multi-criteria decision-making approaches. It can be concluded from the comparative study that there are many uncommon vulnerability parameters amongst each selected method. Apart from this, many important parameters that can severely affect buildings during an earthquake, such as building on a hill slope, pounding effect, large/massive overhangs, etc., were not included in most RVS methods. This resulted in a considerable variation in the final score and ranking of each RVS method. The BMTPC (2012) method has the highest score amongst all methods, which means that one can find significant observations related to each sub-criterion. The method is ranked 1st in multi-criteria-based decision analysis, which indicates that it is the most suitable method. Following the BMTPC (2012) method, the Jain et al. (2010) method has the second-highest score and ranked second. In contrast, the Arya (2003) method has the least score and secured the last rank.

Using the selected RVS methods, a survey was performed on 100 RC buildings in each of the three cities (i.e., Pithoragarh, Gangtok, and Agartala) in India, and the results of RVS methods are compared. It was observed that a set of buildings, when surveyed using different RVS methods, gave different results (i.e., damage grades of buildings). A considerable variation in the results of RVS methods can be observed in each city. It was investigated that the important reason for such varying results is the relative weights assigned to each vulnerable parameter in each RVS method. The vulnerable parameters such as soil type, soft storey, and plan irregularity have different relative weights in each RVS method. Therefore, to have unanimity in the results of different RVS methods, it is necessary to fix the relative weights of each vulnerable parameter. For this purpose, at first, there is a need to understand the effect of individual vulnerable parameters on the building's overall performance and quantify the impact.

The focus of the current study is only limited to the assessment of buildings before an earthquake. During future research, determining the effect of each vulnerable parameters, one may emphasize on validation of results with the performance and the damages observed in buildings after an earthquake. The post-earthquake building damage data can also be used to calibrate and improvement of the selected methods. For a country like India, buildings' damage data only from one location cannot be used to justify the similar behaviour of buildings at other places far from a distance. Therefore, the accuracy of the method will improve only when the damage data of buildings from various locations in the country is considered. Numerical analysis of a building using an appropriate software package can also be used to understand buildings' behaviour more accurately. Such work will lead to more refinement of existing RVS methods. It will also help the new RVS methods, ultimately leading to more accurate and uniform preliminary assessment procedures for buildings.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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