Comparison of building vulnerability assessment methods engineering essay

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A review of vulnerability assessment methods for buildings is conducted out with a view to evaluate their appropriateness for use in seismic risk assessment. A ranking scheme has been developed to ‘ score’ each vulnerability assessment method. The ranking considers general description of vulnerability, building response factors, variance in output, applicability and ease of use, which are the major characteristics for vulnerability assessment tools used in seismic risk assessment. A case study in the older portion of Dhaka city, Bangladesh has been conducted to investigate the efficiency of some state-of-the- art vulnerability assessment methods. The ‘ hybrid’ vulnerability scale, which uses a FEMA 310 and IITK GSDMA approaches score high in the ranking, whilst the other scales based on the Rapid Visual Screening FEMA 154, Euro Code 8, New Zealand Guidelines, Modified Turkish Method and NRCC perform differently in various weighting scenarios. However, it is found that none but the ‘ hybrid’ (which includes the local site specific issues as well as the results from non destructive testing and experimental data) method effectively suits all the criteria essential for their use in seismic risk assessment, especially emphasis on physical vulnerability factors, applicability and variances in output.

Keywords vulnerability assessments, physical vulnerable parameters, seismic risk assessment

1. Introduction

Seismic risk assessment is a vital tool to manage the growing risk in the face of the ever-increasing exposure in highly seismic regions. Due to the changes in the built environment and continuously evolving seismic sciences, it is essential to refine the risk assessment modeling continuously.

In particular, vulnerability of buildings to ground shaking is recognized as a key element in any seismic risk model (Spence et al. 2008). Therefore, seismic vulnerability assessment is an essential tool for governments and individuals to mitigate the consequences of earthquakes. Existing vulnerability assessment methodologies vary with various postulations proposed for the characterization and prediction of earthquake hazard and the methodology used to evaluate building regarding the hazard (FEMA 1999; Bertogg et al. 2002). The development of a region-wide seismic vulnerability assessment framework, such as FEMA 310 for the US (FEMA 1999), requires a unique vulnerability assessment tool to accommodate all the above mentioned issues.

Within this paper, a comparison and critical review of existing vulnerability assessment methodologies for buildings is conducted out, with a view to their utilization in a region-wide seismic risk assessment. A ‘ hybrid’ method consisting of FEMA 310 (FEMA 1999) and IITK GSDMA (Durgesh 2005) has been set up to evaluate vulnerability, combining an analysis of building typologies with expert judgment. Background information on the most significant vulnerability assessment methods are provided in the paper together with their advantages and disadvantages for use in seismic risk assessment. Moreover, the seismic vulnerability for contemporary and historical 93 buildings in old Dhaka City, Bangladesh has been assessed as a case study to show the spatially distributed qualitative risk within the area with the help of different vulnerability assessment tools. Finally, a scoring method is proposed to qualitatively represent the relative rankings of the selected vulnerability assessment tools to find out a suitable uniform approach to be used for seismic risk assessment.

2. Selection of suitable building classification system

Vulnerability can be defined as the susceptibility of buildings to damage in presence of seismic ground motion (Hill and Rossetto 2008). The evaluation of building vulnerability is a basic part of any risk assessment methodology. An accurate, transparent and conceptually sound algorithm for assessing the seismic vulnerability of the building stock is one of the main ingredients in a seismic risk model and indeed over the past 30 years many tools and methodologies have been proposed for this purpose. This study takes an overview on some of the most noteworthy contributions in the field of vulnerability assessment and the key advantages and disadvantages of these procedures have been identified in order to distinguish the main characteristics of an ideal methodology (Calvi et al. 2006). In vulnerability studies, it is essential to differentiate various building types, since, different types of buildings tend to respond in a different way under similar ground motions (Tesfamariam and Saatcioglu 2008). Hence, the buildings should be classified according to their similar dynamic properties, before the conducting a vulnerability assessment of an urban area. The parameters that influence the dynamic response of a structure to ground motion are well recognized, for example, in Euro code 8 (BSSC 2003; CEN 2004), and embrace the structure’s geometrical and material properties. A building classification system that considers a high-degree of segregation in vulnerability studies and an enhanced estimate of the financial losses, has been expressed elsewhere (Carvalho et al. 2002). This study focuses on the dominant building types of the Indian region (Alam et el. 2010), which comprises mainly of reinforced concrete buildings and masonry buildings.

3. Existing seismic vulnerability assessment methodologies: an overview

Table 1 in Appendix A briefly describes each vulnerability assessment tool selected and the rationale for their selection. It is obvious that the review is not extensive; however, the tools have been selected for the predominant building classes as well as to the contemporary practices in seismic vulnerability assessment of buildings. From the literature, it is evident that, there is a lack of unified vulnerability assessment technique, which covers the entire local as well as the global parameters. To cover the location-specific physical components present in both the developed and the developing countries, a ‘ hybrid’ method has been formulated for the vulnerability assessment of existing structures incorporating FEMA 310 (FEMA 1998, 2003, ASCE 1998) and IITK GSDMA (Durgesh 2005) methods. Other vulnerability assessment tools are chosen from a wide range of published and peer reviewed papers in seismology, structural vulnerability, and earthquake engineering fields. Since, most of the tools have been developed for some particular circumstances, such as vulnerability assessment in the field, for structural analysis etc. they may not contain some of the uniqueness specified in the scoring structure. However, they are included in this study, as either elements of these guidelines or tools have been used in past seismic vulnerability assessment of buildings or they illustrate a distinctive characteristic, which is essential in a tool for the seismic vulnerability assessment.

4. Investigation of the suitability of different vulnerability assessment tools: a case study

A case study of 93 buildings of older portion of Dhaka city-the capital of Bangladesh (Alam et al. 2010) has been selected to evaluate the suitability of various vulnerability assessment tools for seismic risk assessment. The predominant structural types, specially associated with medium to high seismicity, present in South Asian countries have been presented in the building classification system. After considering building inventories of different countries of South Asian region, it was found that South Asian building inventory is primarily composed of reinforced concrete buildings and masonry buildings. The study includes Bangladesh (CDMP 2009), Nepal (AUDMP 2007), and India (Durgesh 2005) for classifying major building classes for the area. There exist some other types, such as adobe (mud house), tin-shed housing, timber and steel structures etc, which contribute a very small proportion of the existing inventory with moderate to high seismicity. The premier resolutions of relevant building type sub-categories for the vulnerability assessment are the reinforced concrete frames with and without masonry infill as well as the unreinforced masonry buildings for the study area.

The seismic vulnerability of buildings in the stock varies widely with different vulnerable factors (Hugo 2002). The principal vulnerability factors used in the categorization of buildings in the study area are structure type (the main lateral force resisting system of buildings), number of story, and code level (seismic design standard applied in the design of buildings). Moreover, architectural features which are the parameters for defining geometry of buildings such as story height, span length, presence of open first-storey etc. act as factors for the vulnerability assessment. Several structural features may be considered as the factor affecting vulnerability of buildings. These factors include soft story, heavy overhang, short column, pounding possibility between adjacent buildings, and visible ground settlement. During this study a number of vulnerable factors were identified that are comprehensively discussed here. According to Turkish method (Bommer et al. 2002, Tesfamariam and Saatcioglu 2010), the level of building damage during earthquakes depends on the apparent building quality which is, in turn, related to the quality of construction materials, workmanships and building maintenance. Well-trained observers can classify a building's quality roughly as good, moderate, or poor. Many building collapses during seismic events may be ascribed to the absence of the bracing elements (e. g. available walls in the upper floors) in the ground floor, and hence develop a ground floor soft in the horizontal direction. The plastic deformations at the plastic hinge points of the columns can develop an undesirable sway mechanism with a large concentration of the plastic deformations at the column ends (Hugo 2002). Hence, the soft story buildings exhibit a less safe behavior than the similar regular structures during moderate and severe earthquake. Normally, this situation can be resulted from the building that locates along the side of the main street as the first story is being used for a commercial space that has opening between the frame members for customer circulation. Figure 1 shows some of the examples of soft story (ground floors being used as shop) in Shakhari Bazar, Dhaka, Bangladesh. In addition to soft stories, another vulnerable factor, termed as " heavy overhanging floors" in multistory buildings lead to irregularity in stiffness and mass distributions (Hugo 2002). From the earthquake engineering view point, these irregular plan shapes are undesirable as they cause inappropriate dynamic behaviors when subjected to horizontal earthquake ground motion. Typical heavy overhangs found in the old part of Dhaka City are shown in figure 2. Moreover, the shear failure of short columns is another major cause of building collapse during a seismic event (Hugo 2002). It is also termed as squat columns, i. e. columns having relatively high thickness compared to their height, and most of the cases are fixed in strong beams or slabs. By unintentional addition of parapet infill in frame structures, slender columns can also be converted into short columns. In case of short columns with significant bending capacity, enormous moment gradient can develop a large shear force under horizontal actions of a seismic event, which generally leads to a shear failure before the plastic moment capacity is being reached (Hugo 2002). It was observed after the August 17th, 1999 earthquake in Turkey (Mw= 7. 4) that a large number of buildings were damaged due to the presence of short columns (Saatcioglu et al. 2001). Damage due to pounding can also be observed after almost every earthquake events. Different vibration periods and non-synchronized vibration amplitudes cause the close buildings to knock together. Buildings subjected to pounding receive heavier damage on higher stories (NZSEE 2000, 2003). Topographic amplification may also increase ground motion intensity on hilltops during earthquake; hence, this factor should be taken into account in the seismic risk assessment. In the last not the least, building shape and elevation are major factors affecting buildings during an earthquake. It was evident from the experience of different seismic events, that the buildings with irregular shape are more damaging than the buildings of regular shape (Hugo 2002).

Similarly elevation of building is also another important factor responsible for structural/building damage during an earthquake. Narrow tall buildings are more vulnerable during an earthquake (Hugo 2002). Figure 3 shows vertical irregularity of an existing building in the study area.

There exists a numerous numbers of vulnerability assessment techniques, that utilize various types of vulnerability factors. Table 2 summarizes different vulnerability factors, which are frequently, used in different seismic vulnerability assessment techniques utilized in the study. From this study, it can easily be identified that some of the seismic vulnerability assessment techniques are very robust, e. g. FEMA 310, FEMA 154 etc, whereas in case of some other methods, (e. g. Euro Code 8) some of the major vulnerability parameters are not clearly defined.

The results from the assessment of 93 buildings in the study area are depicted in the figure 4. For risk evaluation, it is required to collect, analyze and properly match a huge quantity of data. Geographic information system (GIS) can effectively be utilized to manage and overlay the information levels and graphical output of the results (Codermatz 2003). Therefore, a geographical information system (GIS) database has been developed to represent the spatial distribution of the vulnerable buildings for different assessment techniques within the study area. Figure 5 shows the distribution of vulnerable buildings in GIS environment, resulted with the use of FEMA 154 method, which shows that most of the buildings fall under very high risk group. Whereas, the distribution of risk classes within the buildings are in a wide range in case of hybrid method, depicted in figure 6. The distribution of vulnerable buildings assessed by Euro Code 8 and NRCC are also presented in figure 7 and figure 8 respectively, which show comparatively lower risk variances.

5. Vulnerability assessment methodology scoring system

The general description of vulnerability assessment methods which include the input variables, are very useful for the people involved in the field directly, where as the information about physical measurable parameters are necessary for the detailed analysis of a structure and the decision makers utilize the description of output for generating an effective decision (Hill and Tizina 2008). A reliability or performance scoring system has been developed to rank the vulnerability assessment methodologies according to the criteria mentioned above. The proposed scoring system consisting of 3 main sections with 17 sub-categories is depicted in Table 2 of Appendix A. The score obtained in each of the 3 sections is given equal weighting in the computation of the total reliability score for vulnerability assessment. The system tries to reduce most of the subjectivity implicated in the ranking of different vulnerability assessment methods. Since, some subjectivity has been utilized to assign the categories, the resultant scores can be utilized only as a qualitative representation of performance or reliability. To provide a clear indication of each methodology's performance or reliability, an affirmative score is given as 3 points, a moderate score is given as 2, a negative score 0 point, whereas the method partially fulfills the requirement is given 1 point. Since, experimental value provides data based on ' real-life' experiences, it is more preferred in the scoring system. Analytical and judgment-based values are considered as second and third best respectively. For the sub-categories, the scoring is based on the Table 3 of Appendix A.

This scoring for reliability or performance has been applied to the vulnerability assessment methods applicable for mainly reinforced concrete buildings as well as unreinforced masonry building types.

Category A of the scoring system in Table 2 deals with the basic input description of vulnerability assessment tools, i. e. ease of measurement (Saatcioglu, et al. 2001), range of buildings types covered (FEMA 2002, ASCE 2003, UNDRO 1980), site specific factors, including local and global aspects regard (ASCE 2003, ASCE 1988, NRCC 1993, Durgesh 2005) . This is important for the people working in the field measurement.

In category B mostly physical measurable vulnerability factors have been considered, which is very useful for analyzing the structural behavior. It deals with the scope of vulnerable parameters (ASCE 2003), quantity of database (ATC 2004), applicability of tools as non-structural components of the structures (NRCC 1993).

Finally category C of the proposed scoring system utilizes the involvement of the output factors, which encompasses the well defined vulnerability scales (FEMA 2002) (ASCE 2003), risk variances (ASCE 2003, Durgesh 2005), impact of non-structural components as well as the adoptability (NRCC 1993). This category mainly focuses on the preferences for the decision makers.

For different specific needs, risk assessment specialists may prefer different weightings on the scoring categories. The categories are weighted according to four different scenarios (I-IV) as depicted in Table 4 of Appendix A. These weightings give a maximum score of 51 points in each case which are only for illustrative indication.

An example of use of the proposed scoring method is given in Table 5 of Appendix A. The final ranking for the vulnerability assessment tools considered is shown in Table 6 of Appendix A. The individual scores are given in Table 7 of Appendix A

6. Discussion on vulnerability assessment method scoring

This section discusses about the performance of different vulnerability assessment tools in different scoring categories in wider aspect for all the weighting scenarios proposed. At this point it is essential to re-state that the vulnerability assessment ranking reflects how appropriate the method is for use in seismic risk assessment. To rank the techniques, several weighting scenarios have been utilized with the calculated scores. For weighting scenario I, equal weighting for each category was adopted which provides an overall view of the vulnerability assessment method's performances. The authors' believe that each of the identified features is equally important and it is suggested that proposed scoring system utilizes this weighting scenario. ' Hybrid" method, NRCC (NRCC 1993) guidelines and FEMA 154 (FEMA 2002, ATC 1998) rank the top three positions for the weighting scenario I. The ' Hybrid" method contains detailed descriptions for different classes of buildings and has a well defined methodology for calculating physical vulnerability factors. The ASCE 31 standard (FEMA 310) is not a building code. It is a method of evaluating existing buildings to determine if they meet seismic performance objectives such as Life Safety or Immediate Occupancy. NRCC guideline follows the similar principles as the ' hybrid' one; however, the calibration for building typology for NRC guidelines considers the Canadian construction practice. Fundamentally, the score (seismic priority index) in NRCC is related to the seismic risk for a particular building, given the occurrence of an earthquake equivalent to that specified in the National Building Code of Canada (NRCC 1993). It is to be used as an initial assessment for deciding which building should have more detailed evaluation in order of priority. Moreover, the effect of torsional irregularities has not been taken in to account. In FEMA 154, the score was affected by the lack of sufficiently detailed analysis; rather it encompasses a rapid visual screening method (FEMA 2002). The use of seismicity regions, rather than site-specific seismic hazard data, for the Rapid Visual Screening (RVS) procedure substantially reduces the accuracy of results because the calculations use levels of ground motion which differ from the levels of ground motion at all sites except those where ground motions are at the median value for a seismicity region. Thus, RVS final scores are systematically shifted and overestimate the level of risk for locations with below-median ground motions and underestimate risk for locations with above median ground motions.

In case of weighting scenario II, more weighting is given to general description of vulnerability to highlight the methods suited for in-field measurements. For weighting scenario II, again the same results happened, i. e. ‘ Hybrid’ one out ranked all other approaches.

For weighting scenario III, more weighting values have been given to the physical vulnerable parameters.

And in case of scenario IV, weighting has been given to the variance in output. For this purpose, a case study of 93 buildings of old Dhaka city of Bangladesh has been conducted. In this case study, different types of buildings have been assessed with various methodologies. Here, Hybrid and NRCC Guidelines ranked the 1st where as FEMA 154 (FEMA 2002, ATC 1998) and NZ Code ranked 2nd and 3rd. The variation and the results of the assessment have been depicted in Figure 5 through Figure 8.

In weighting scenario V, more conscious was given to Canadian present construction practices (Cook 1999, Onur et al. 2004). Here, the ‘ Hybrid’ as well as the NRCC method outranked the other methods.

7. Scoring Summary with Different Multi Criteria Decision Making Tools

The proposed scoring system is a wide-ranging tool to compare different vulnerability assessment methods in the context of ease of use and applicability. It cannot catch all the parameters, but qualitatively gives a better indication of the suitable seismic vulnerability assessment method for buildings. First of all, it can be remarked that, the positions of the methods in the ranking change markedly between the different weighting scenarios. Of the considered seismic vulnerability assessment methods, it is seen that the “ Hybrid” method composed of FEMA 310 (FEMA 1998, 2003, ASCE 1998) and IITK-GSDMA outperforms other vulnerability assessment in all respects. However, NRCC (NRCC 1993) method also performs adequately, where the guideline was developed specifically with Canadian buildings in mind, though certain features are lacking within the description of detailed analysis. Nonetheless, for all the weighting scenarios, the proposed “ hybrid” method performs well and should be considered as the preferred alternative. Moreover, the presence of FEMA 154, Euro Code 8(Milutinovic and Trendafiloski 2003, CEN 2004) and New Zealand Guidelines (NZSEE 2000, 2003) in the ranking system are notable. However, it is clear that the methods do not capture a sufficient quantity of characteristics that are required of such a guideline for the particular weighting scenarios.

In this study different multi criteria decision making tools (e. g. AHP. Elctre I Is, and TOPSIS) have been utilized to find out the suitable most alternative. The Analytical Hierarchy Process (AHP) is a decision-aiding method developed by Saaty (Saaty 1980). The main goal of AHP is to quantify the relative priorities for a given set of alternatives on a ratio scale, based on the judgment of the decision-maker, and stresses the significance of the perceptive judgments of a decision- maker as well as the consistency of the comparison of alternatives in the decision-making process (Saaty 1990). Whereas ELECTRE I (Benayoun et al, 1966; Roy 1971) is an overall method of ranking alternative systems in the presence of qualitative criteria. The idea in this algorithm is to choose those nodes (i. e. alternative systems) which are preferred for most of the criteria and yet do not cause an unacceptable level of discontent for any one criterion. Moreover in case of TOPSIS (Technique for Order preference by Similarity to Ideal Situation) method, the selected alternative should be as close to the ideal solution as possible and as far from the negative-ideal solution as possible. The ideal solution is formed as a combination of the best performance values revealed in the decision matrix by any option for each attribute. The negative-ideal solution is the combination of the worst performance values. Propinquity to each of these performance poles is measured in the Euclidean sense (e. g., square root of the sum of the squared distances along each axis in the “ attribute space”), with elective weighting of each attribute (Olson 2004).

By utilizing Electre I Is (Hwang and Yoon 1981) and Analytical Hierarchy Process (Yang and Lee 1997); it was found that the proposed “ hybrid” method outranks all the methods in all cases (Figure 10 and Figure 11). Finally TOPSIS method (Chu 2002) has validated the same decision about the proposed “ hybrid” method to be the preferred one.

In the context of decision making and field measurement, “ hybrid” method consisting of FEMA 310 (FEMA 1998, 2003, ASCE 1998) and IITK-GSDMA is recommended. Whereas, if the rapid assessment of buildings is the major concern, vulnerability assessment through FEMA 154 (FEMA 2002, ATC 1998) and NRCC (NRCC 1993) guidelines should also be considered as the preferred options.

8. Conclusion

This study has identified significant characteristics that should be included for an appropriate seismic vulnerability assessment method of buildings. A scoring system has been proposed for the qualitative review of various vulnerability assessment techniques and a particular attention was given to potential use in Canada. It is found that a vulnerability assessment technique termed as “ hybrid” method i. e. combination of FEMA 310 (FEMA 1998, 2003, ASCE 1998) & IITK GSDMA (Durgesh 2005) ‘ captures’ characteristics to a wider degree that a suitable vulnerability assessment method should posses. However, the proposed ‘ hybrid’ method is calibrated with the data from US and Bangladesh, which can be applied to other regions with slight modifications.

In seismic risk assessment, the building vulnerability assessment depends on data from many sources, amongst which, the past earthquake damage survey data are of major concern. Existence of various vulnerability assessment approaches, raises concern over worldwide to have a simplistic effective vulnerability assessment tool, to be useful world-wide. The authors' believe that the proposed " hybrid" method provides a robust basis for vulnerability interpretation and recommended future studies of vulnerability assessment method to combine more consistent and wider descriptions of the parameters for use in seismic risk assessment.

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