A Workshop on Microzonation

Methodology for Seismic Vulnerability Assessment of Building Stock in Mega Cities

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Abstract

The damage to built environment during recent earthquake in India has demonstrated the need for seismic risk assessment that is capable of predicting the consequences of earthquakes. The collapse of man-made engineered and non-engineered buildings during an earthquake is the chief contributor to the loss of lives and injuries to the people. Vulnerability Atlas of India states that there are about 11 million seismically vulnerable houses in seismic zone V, while the corresponding figure for seismic zone IV is 50 million. In all, there are about 80 million building units in India, which are vulnerable, and pose unprecedented risk, if earthquake strikes. The greatest challenge, therefore, is not only to rehabilitate these vulnerable houses so as to reduce considerable loss to human life and property but also to evolve an accepted methodology in Indian context to estimate/quantify the seismic vulnerability of the existing built environment, which will be provide a useful information for policy making.

The paper proposes an approach to estimate seismic vulnerability of existing buildings of a city in Indian context. The scheme estimates seismic vulnerability of existing building stock quantitatively and qualitatively. The quantitative approach covers demand-capacity computation, while qualitative procedure estimates structural scores based on national & international state-of-the-art procedures viz. Rapid Screening Procedure (RSP). The methodology presented would lead to identify buildings that might pose risk in the event of damaging earthquake and would form an integral part of microzonation studies being taken up for Indian vulnerable cities.

Preamble

The rapid growth of Indian cities in the recent past, have accelerated pressure on housing industry, especially in high seismic zone i.e. Zone-IV & V[16]. The built environment in these zones have been seismically found vulnerable as most of these construction are without earthquake resistant measures. The Indian cities are dotted with all kinds of buildings and infrastructural facilities comprising of very good construction to poorly designed & constructed ones. The most challenging task is to evaluate seismic safety of these constructions and take necessary steps for their retrofitting so as to protect them from future earthquakes. Assessment of seismic vulnerability of existing building stock in urban areas would help in disaster mitigation and management by planning mitigation measures before an earthquake strikes.

Seismic vulnerability is a measure of the seismic strength or capacity of a structure[14], hence it is found to be the main component of seismic risk assessment. The review of the built environment for seismic vulnerability estimation is normally carried out in the light of earthquake resistance of buildings, past earthquake damage history & repair thereof, construction practices being adopted, building typology, seismic zoning of the area, building samples, detailed survey of selected buildings, and creation of database and its quantitative and qualitative analysis. The quantitative approach covers demand-capacity (DCR) computation, while qualitative procedure estimates structural scores for buildings and is known as Rapid Screening Procedure (RSP).

Building Typology

The existing building stock of Indian cities is a rich mix of several different building types & construction technologies. The most commonly used building typology are (1)reinforced concrete frame building with infill brick walls (Type-C); (2)brick masonry buildings with reinforced concrete roofs and using cement mortar in most of the case and mud/lime mortar in few of buildings (Type-B); (3)buildings made of GI sheets, thatch and other light weight and cheaper materials (Type-A). The first two categories, fall under engineered construction in which assistance from qualified structural engineers are sought at each stage in most of the cases, while the third category is governed with socio-economic consideration rather than engineering one and falls under non-engineered construction.

Seismic Vulnerability Assessment

In order to estimate seismic vulnerability of existing building stocks on a wide spread area, it is imperative to make several assumptions for selection of building samples, analysis and determine the damage levels. The present approach assumes the following:

- It is conceivable that the study area would experience earthquake with damage greater than intensity VII+, in zone IV & V, the level assumed by the IS-1893:2002 (Part-I) for design purpose.[16]
- The building stock under consideration is expected to behave as per known performance of each type of structure under earthquakes.
- The consequences of an earthquake causing building damage due to other disasters such as fire, floods are ignored.
- For effective categorization, various building typologies assumed are : Type-A: Buildings in field-stone, rural structures, unburnt brick house, clay houses; Type-B: Ordinary brick building, buildings of the large block and prefabricated type, half-timbered structures, building in natural hewn stone; Type-C: Reinforced building, well built wooden structures. [16,18]
- It is well nigh possible to carry out survey of all existing buildings from seismic vulnerability point of view. In order to restrict building survey on limited buildings of study area, fair number of representative building samples of different types are selected from various pockets / colonies for detailed investigations. The various pockets are different municipal wards as delineated by municipal authorities.
- Appropriate, structural scores have been assigned for various seismic vulnerability parameters, based on the performance of different types of building in past earthquake in Indian context. The structural scores have been derived after validation of its results on the building sample considered for deriving isoseismial map by different agencies after Jabalpur earthquake of 1997.[23,24]

Methodology for Assessment of Seismic Vulnerability

Existing buildings can become seismically deficient since seismic design code requirements are constantly upgraded and there is continuous advancement in engineering knowledge. Indian buildings built over past two decades are seismically deficient because of lack of awareness regarding seismic resisting measures. Also seismic design is not normally practiced in most of the buildings being built. In India. Therefore, seismic vulnerability estimation is pre-requisite for disaster mitigation & management.

Vulnerability estimation is a complex process, which has to take into account not only the design of building but also the deterioration of the material and damage caused to the building, if any. The difficulties faced in seismic vulnerability estimation of a building are manifold. There is no reliable information/database available for existing building stock, construction practices, in-situ strength of material and components of the building, and therefore, seismic vulnerability estimation mainly relies on set of general evaluation statements. For earthquake load definition, ground motion parameters available in present code (IS:1893-2002) can be taken, if site dependent accentuations are not available for the area. As regards the effect of local soil conditions, which are known to greatly modify the earthquake ground motion, and data given in code on site response will have to be considered.

The quantitative approach, outlines here covers demand-capacity computation primarily based on ATC-40, 1996 [10,13,14], while qualitative procedure estimates structural scores based on national & international state-of-the-art procedures viz. Rapid Screening Procedure (ATC-21, 1988, ATC-21-1, 1988)[7,8]. The general procedures for seismic vulnerability estimation of existing buildings proposed are site visit & data collection; selection & review of evaluation statements; follow-up fieldwork; and analysis of buildings by quantitative and qualitative approach.

Quantitative Approach: Demand-Capacity Approach

The approach is a comparison between some measures of demand that the earthquake places on a structure to a measure of capacity of building to resist. The Demand/capacity ratio (DCR), thus evaluated is measure of earthquake resistance of a building. The DCR less than unity indicate the building is safe for respective stresses under consideration. However, any DCR exceeding one, indicates that building is vulnerable to earthquake loads as defined in IS:1893-2002. DCR computation for masonry and RC buildings are discussed hereunder.

DCR Computation for Masonry Buildings

Demand

All building components under evaluation should be able to resist the effects of the seismic forces as prescribed in IS-1893-2002.[16] The design seismic base shear (V_B) calculated as per codal provisions is the basic seismic demand placed on the structure by seismic ground motion in a particular zone.

Design Seismic Base Shear

The design seismic base shear is the total design lateral force at the base of a structure. The total design lateral force or seismic base shear (V_B) along any principal direction shall be determined by the following expression

$V_B = A_h \text{ x } W$

Where, A_h is design horizontal acceleration spectrum value, calculated from the following equation

$$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$$

where

Z = Zone factor, 0.24 for Delhi (Zone-IV)

I = Importance factor

R= Response reduction factor

S_a/g= Average response spectra coefficient, based on time period, and

W = Seismic weights of all the floors of building. The detailed explanation is given in IS-1893-2002 (Part-I).

Fundamental Natural Period

The approximate fundamental natural period of vibration (T_a), in second for moment resisting frame buildings with brick infill panels may be estimated by the empirical expression:

$$T_a = \frac{0.09\,h}{\sqrt{d}}$$

where,

h = height of building, in meters and

d = base dimension of building at plinth level, in m along the considered direction of the lateral force.

The designed base shear computed (V_B) will be distributed along the height of the building as per the following expression:

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{i=1}^{i=n} W_i h_i^2}$$

where,

Q_i = designed lateral force at floor i

W_i = seismic weight of floor i,

h_i = height of floor I measured form base, and

n = number of storeys in the building is the number of levels at which the masses are located

Average Shear Stress

The average shear stress ($V_{avg,i}$) of a building at any level is derived by following expression:

$$v_{avg,i} = \frac{Q_i}{A_w}$$

where,

Q_i = storey shear at the level under consideration determined

A_w = summation of the horizontal cross sectional area of all shear walls in the direction of loading. The wall area shall be reduced by the area of any openings.

Direct & Bending Stresses

The total horizontal shear (Q_i), at any level be distributed in various walls in proportion to their shear stiffness. This shear causes bending moment equal to (Q_i h_i / 2) at the top and bottom section of the wall where h_i is the height of wall. The bending moment will cause bending stress ($\sigma_{b,i}$) in addition to the direct stress ($\sigma_{d,i}$) due to dead load of the building above the floor level under consideration[17].

$$\sigma_{t/c,i} = \sigma_{d,i} \pm \sigma_{b,i}$$

Overturning Moment

The total horizontal shear (Q_i) also causes overturning moment (M_o) in the walls, which is equal to (Q_i h_i / 2) at the bottom of wall, as per clause 8.2.5 of IS:4326-1993, whereas free standing walls shall be checked against overturning under the action of design seismic force allowing for a factor of safety of 1.5. The factor of safety against overturning is given as under:

$$FOS_i = \frac{M_s}{M_o}$$

where, M_s = stabilizing moment due to dead load at the bottom of wall

Capacity

The capacity of a masonry wall is its allowable stress depending upon mortar type in accordance with relevant codal provisions (IS: 1905-1987).

Shear Stress

The permissible shear stress calculated on the area of bed joint shall be in accordance with clause 5.4.3 of IS:1905-1987, and is reproduced here under: [17]

$$f_s = 0.1 + f_d / 6$$

where, f_d = compressive stress due to dead loads

Permissible Compressive & Tensile Stress

The permissible compressive (f_b) stresses shall be based on the values given in Table-8 of IS:1905-1987, after multiplying with appropriate reduction & modification factors (clause 5.4, IS:1905-1987).

The permissible tensile stress (f_t) shall be as per clause 5.4.2, IS:1905-1987.

Demand – Capacity Ratio (DCR)

Based on above, DCR computation for various parameters viz. shear stress, compressive & tensile stress, and overturning are to be performed for assessing vulnerability of masonry building as under:

$$DCR - ShearStress = \frac{V_{avg,i}}{f_s}$$

$$DCR - Tensile \quad Stress = \frac{\sigma_{t,i}}{f_t}$$

$$DCR - Compressive \quad Stress = \frac{\sigma_{c,i}}{f_b}$$

$$DCR - Overturning = \frac{1.5}{FOS_i}$$

DCR Computation for RC Buildings

The proposed DCR computation for RC buildings comprises of two stages:

Input Data Stage:

Step 1: Study of soil conditions at the site.

Step 2: Measurements of actual geometry of building and its components.

Step 3: Non-Destructive Testing (NDT) to estimate actual strength of concrete in the building components, if possible

Step 4: Tests to estimate extent of corrosion to carefully estimate their available diameters and verify the size, number and spacing of reinforcing bars, if possible.

Analysis Stage:

Step 5: Preparation of 3-D model of building frame, using measured geometry, and material properties.[22]

Step 6: Estimation of design lateral force on building using IS 1893-2002 (Part-1) for 5% damping.

Step 7: Application of design lateral force on 3-D building model to determine stress-resultants (i.e. axial forces, shear forces, bending moments) in the beams & columns and determination of inter storey drifts.

Step 8: The most critical stress resultants thus obtained for the various RC members are the demands for the members

Step 9: Determination of RC member flexural & shear capacities with actual cross section geometry & material properties as per IS 456-2000 and Demand/Capacity ratios of RC members at critical locations.[5,15,16,22]

The DCR less than unity of any member indicate that the member is safe, however, any DCR exceeding one, indicates that the member is vulnerable.

DCR Computation for Non-Structural Elements : Parapet Walls

Non-structural falling hazards such as chimneys, parapets, cornices, veneers, and overhangs can pose life safety hazards if not adequately anchored to the building. The maximum height of unbraced URM parapet above the roof should not exceed 1.5 times the thickness of parapet wall. Accordingly, DCR for parapet walls can be computed by comparing height with 1.5 times thickness of parapet wall.

Qualitative Approach : Rapid Screening Procedure (RSP)

The Rapid Screening Procedure (RSP)[7,8] is aimed for identifying potentially hazardous buildings in the study area, without going into detailed analysis. RSP utilizes a methodology based on visual inspection of a building and noting the structural configuration. The methodology begins with identifying the primary structural lateral load resisting system and materials of the building. The method generates a Structural Score ‘S’, which consists of a series of ‘scores’ and modifiers based on building attributes that can be seen during building survey. The Structural Score ‘S’ is related to probability of the building sustaining life-threatening damage should a severe earthquake in the region occur. A low S score suggests that the building is vulnerable and needs detailed analysis, whereas a high ‘S’ score indicates that the building is probably safe for defined earthquake loads. Thus, the expression for structural score is:

S (Structural score) = BSH (Basic Structural Hazard) + PMFs (Performance Modification Factor)

Basic Structural Hazard (BSH) & Performance Modification Factors (PMFs)

Each building type is assigned with basic structural hazard (BSH) score. This BSH reflects the estimated likelihood of a typical building of that category sustaining major damage given its seismic environment. ATC-21-1988 and ATC-21-1-1988, presents BSH for various building types applicable to state of California. These scores have been suitably modified in Indian context, based upon 1997 Jabalpur earthquake damage survey data.[12,23,24,25] These values have been determined so that the seismically good building has a high value, and a potentially weak/hazardous building has a low value. The BSH scores estimated for Type-A, Type-B, and Type-C are 2.0, 2.5 and 3.0 respectively.

In order to arrive at final structural score ‘S’ for the building under review, a series of Performance Modification Factors (PMFs) are subtracted from BSH. These PMFs account for significant factors such as high rise, quality of construction, vertical & plan irregularities in the structural system, soft storey, pounding, cladding, soil/ground condition and ambience, that can negatively affect a building’s seismic performance or adequacy. There are number of factors that can modify the seismic performance of a structure causing the performance of an individual building to differ from the average. These factors basically are related to significant deviations from the normal structural practices or conditions, or have to do with the effects of soil amplification on the expected ground motion. The number and variety of such performance modification factors, for all types of buildings is very large. However, based on experience gained during the damage survey in past earthquakes, a limited number of the most significant factors were identified. These PMFs (Table-I) were assigned values based on judgment such that when subtracted to BSH, the resulting modified score would approximate the possibility of major damage.

Table-I Performance Modification Factors

Modifiers	Description	Modification Factor
High Rise	Upto 2 storey	0
	Between 3 - 7 storey	-0.2
	More than 7 storey	-0.5
Quality of Construction	High	0
	Medium	-0.25
	Low	-0.50
Vertical Irregularity	Steps in elevation, inclined walls, discontinuities in load path, building on hills	-0.50
	Without vertical irregularity	0
Soft Storey	Open on all sides of buildings, tall ground floor, buildings on stilts	-0.50
	Without soft storey	0
Plan Irregularity	"L", "U", "E", "T", or other irregular building shape	-0.50
	Without plan irregularity	0
Pounding	Floor levels of adjacent buildings not aligned and less than 100 mm of separation per storey	-0.50
	Without pounding	0
Cladding	Many large heavy stone or concrete panels, glass panels and masonry veneer do not qualify	-0.50
	Without vertical irregularity	0
Soil Condition	Buildings founded on rocks (SR)	0
	Buildings founded on cohesionless soil (SC)	-0.3
	Buildings founded on black cotton soil (BC)	-0.6
Ground Condition & Slope Ambience	Buildings in flat/plain land domain	0
	Buildings on hill slopes/tank bunds/reservoir rims with slope > 10^o - gentle	-0.10
	-do- - moderate	-0.20
	-do- - steep	-0.30

Generally speaking if a building's structural score 'S' is less than 2, then the seismic performance of building may not meet the codal requirements. Hence, such buildings are classified under vulnerable buildings in the present study recommended for detailed investigations.

Discussion

The pragmatic methodology for deterministic vulnerability analysis of built environment has been attempted here with an objective to generate seismic vulnerability map of buildings of Indian Cities. Intensive field survey can be conducted by filling a comprehensive questionnaire. The sample buildings are qualitatively explored for ascertaining PMFs pertaining to specific structure, soil & ground ambience. As regards to quantitative estimation of vulnerability of buildings, empirical methods as stated in IS:1893-2002 & IS:1905-1987 have been followed. In order to evaluate demand placed on structure vis-à-vis structural capacity, Demand Capacity Ratio (DCR) on various parameters like shear stress, compressive/bending stress, overturning of walls, and damage to non-structural members attributing to possible failures viz. excessive cracking, falling of walls, falling hazard, and its combination thereof, are calculated for Type B structures. Similarly, DCRs in terms of flexure, shear, falling hazard of non-structural member (parapet wall), attributing to possible failures viz. excessive cracking, diagonal cracking, falling hazard, and its combination thereof, are computed for Type-C structures.

The authors experience based on the seismic vulnerability analysis of buildings carried out in Delhi and Jabalpur cities indicate that dwellings of Type-A category, are constructed based on socio-economic consideration and lack seismic resistant measures and deemed to be seismically vulnerable. As these dwellings mostly constructed of light weight material for roofing, it would result in relatively low casualty, even after their failure.

The vulnerability analysis for masonry & RC buildings can play an important role in selection of strategies for repair/rehabilitation of existing building of a city. In order to reduce the consequences of a major earthquake in Indian cities, it is necessary that appropriate structural as well as non-structural measures be undertaken in building construction.[13,14,19,20,21] The structural mitigation measures are those that directly influence the performance of building stock through strengthening of code provisions and the prevalent construction practices. The vulnerability of any building type can be reduced by incorporating the appropriate structural mitigation measures. The non-structural mitigation measures include improvement in the state of preparedness before a disaster. Further, the impact of introduction of strengthening measures will not only affect the new constructions that are designed and built in future but also assist in reducing risk associated with existing building stock.

Conclusion

The paper presents methodology for estimation of seismic vulnerability of Indian City taking into account as built information, prevalent construction practices, material of construction, quality/workmanship of construction, types of buildings, ambience, geological / geotechnical parameters and is based on ground realities. The developed procedure can be readily applied to any urban region of our country in order to assess the necessity of more detailed investigation for earthquake damage scenario prediction. The methodology can be implemented to estimate seismic vulnerability of different types of existing building stock in Indian Cities and further extended to investigate the impact of mitigation measures on the consequences of an earthquake.

Based on the vulnerability analysis, risk in the form of casualties and economic losses can further be estimated after collecting wardwise demographic and census information for a city. Further, the vulnerability studies demands special attention with reference to heritage/monumental buildings, lifelines like rail/road, water supply, electric supply, sewage, communication, dams, hospitals & schools, vulnerable industries. Also there is a need to identify safe zones/domains/structures and secure routes to work as a relief centers and relief dispersion on incidence of future disaster.

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