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Seismic vulnerability of some historical masonry mosques in Bangladesh

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ABSTRACT: Ancient masonry structures are particularly vulnerable to dynamic actions, especially seismic actions. Although no major earthquakes occur in this country in the last few decades, during the past large earthquakes the masonry structures of this country behaved poorly. This paper presents a contribution to the safety assessment of historical masonry mosques located in different districts of Bangladesh. The approach used here aims at a simple, fast, and low cost procedure suggested by Lourenco and Oliveira based on a simplified geometric approach for immediate screening of the large number of mosques at risk. The proposed geometrical indices of monuments are compared with the respective seismic hazard, expressed by the PGA. The objective is to evaluate the possibility of adopting simple indexes related to geometrical data as a first (and very fast) screening technique to define priority for further studies.

1 INTRODUCTION

In 1897, an earthquake of magnitude 8.7 caused serious damages to buildings in the northeastern part of India (including Bangladesh) and 1542 people were killed. The epicenter was at 230 kms from Dhaka City. During this earthquake almost all existing masonry structures of Bangladesh were either partially or fully destroyed. Figure 1 presents an isoseismal map showing the area under which the masonry structures were affected (Ansary & Noor 2005).

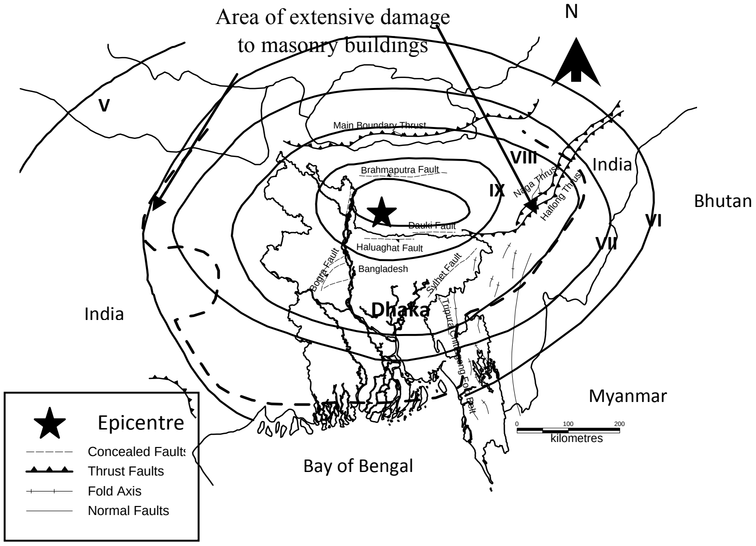

Figure 1. Isoseismal map of 1897 Great Indian earthquake (Ansary & Noor 2005)

Ancient masonry structures are particularly vulnerable to dynamic actions, especially seismic actions. South Asian Cities are particularly at risk due to the large number of ancient monuments (temples, mosques, churches etc.) and dwellings. Due to the ageing process and environmental factors, many cultural heritage buildings, as structures planned and constructed in the past, are vulnerable to dynamic loads, which may unpredictably induce a collapse of a portion of the building or drive the whole structure to a rapid failure. However, the high vulnerability of historical masonry buildings to seismic actions is mostly due to insufficient connections between the various building parts (masonry walls, timber beams on the floors and timber beams on the roof). This characteristic leads to overturning collapse of the perimeter walls under seismic horizontal acceleration. So, the seismic vulnerability assessments are essential to care for historical masonry structures (mosques, temples, churches and dwellings etc.) in Bangladesh.

The approach followed (Laurenco & Oliviera 2004) proposed in this paper aims at a much more simple, fast, and low cost procedure based on a simplified geometric approach for immediate screening of the large number of buildings at risk. The objective is to evaluate the possibility of adopting simple indices related to geometrical data as a first (very fast) screening technique to define priority for further studies with respect to seismic vulnerability. These fast techniques are to be used without actually visiting the buildings, being therefore not accurate. It is expected that the geometrical indices could detect cases in serious risk and, thus, define priority for studies in countries/locations without recent earthquakes. The historical buildings considered at possible risk may deserve more detailed studies using advanced computer simulations, together with adequate material and structural characterization; see ICOMOS (2001).

In the case of urban areas, and in spite of the diversity, a common matrix can usually be established for the seismic areas, more structural than technological. This consists of low building height (up to three stories), moderate spans (maximum of four or five meters), and large thickness of the walls (Giuffrè 1995, Lourenco & Oliviera 2004). Twenty eight mosques from Chapainawabnganj, Jhenidah, Dhaka, Bagerhat, Munshiganj, Sonargaon, Rajshahi, Dinajpur, Bogra, Tangail, Kishoreganj, Barisal and Noakhali districts of Bangladesh have been selected and analyzed considering six Indices of simplified method analysis in this paper.

2 METHODOLOGY

The analysis of historical masonry constructions a highly complex task; namely, because (a) geometry data is missing; (b) information about the inner core of the structural elements is also missing; (c) characterization of the mechanical properties of the materials used is difficult and expensive; (d) mechanical properties exhibit large variability due to workmanship and use of natural materials; (e) core and constitution of structural elements present significant changes associated with long construction periods; (f) construction sequence is unknown; (g) existing damage in the structure is unknown; (h) regulations and codes are nonapplicable. Moreover, the behaviour of the connections between masonry elements (walls, lintels, arches and vaults) and masonry elements and timber elements (roofs and floors) is usually unknown. All these factors indicate that the quantitative results of structural analysis must be looked at with reservation, in the case of vertical loading and, even more carefully, in the case of seismic action. Therefore, more complex and accurate methods do not necessarily correspond to more reliable and better analyses.

The usage of simplified methods of analysis usually requires that the structure is regular and symmetric, that the floors act as rigid diaphragms, and that the dominant collapse mode is in-plane shear failure of the walls (Meli 1998). In general, these last two conditions are not verified by ancient masonry structures, meaning that simplified methods should not be understood as quantitative safety assessment but merely as a simple indicator of possible seismic performance of a building. The following simplified methods of analysis and corresponding Indices are considered.

In-plane Indices:	Out-of-plane Indices:
- Index 1: In-plan area ratio	- Index 4: Slenderness ratio of columns
- Index 2: Area to weight ratio	- Index 5: Thickness to height ratio of columns
- Index 3: Base shear ratio	- Index 6: Thickness to height ratio of perimeter walls

These methods can be considered as an operator that manipulates the geometric values of the structural walls and columns and produces a scalar. As the methods measure different quantities, their application to a large sample of buildings contributes to further enlightening on their application. As aforementioned, a more rigorous assessment of the actual safety conditions of a building is necessary to have quantitative values and to define remedial measures, if necessary.

2.1 *In-plan area ratio*

The simplest index to assess the safety of ancient constructions is the ratio between the area of the earthquake resistant walls in each main direction (transversal Y means EW and longitudinal X means NS, with respect to the central axis of the mosque) and the total in-plan area of the building. According to Eurocode 8 (CEN-EC8

2003), walls should only be considered as earthquake resistant if the thickness is larger than 0.35 m, and the ratio between height and thickness is smaller than nine. The first index, $\gamma 1,i$ reads:

$$\gamma 1,i = A_{wi} / S \qquad (1)$$

where, A_{wi} is the in-plan area of earthquake resistant walls in direction "i" and S is the total in-plan area of the building. The nondimensional index, $\gamma 1,i$ is the simplest one, being associated with the base shear strength. Special attention is required when using this index as it ignores the slenderness ratio of the walls and the mass of the construction. Eurocode 8 recommends values up to 5–6% for regular structures with rigid floor diaphragms. In cases of high seismicity, a minimum value of 10% seems to be recommended for historical masonry buildings (Meli 1998). For simplicity sake, high seismicity cases can be assumed as those where the peak ground acceleration for soft soils, established for a 475 y.r.p., is equal or larger than 0.20g.

2.2 *Area to weight ratio*

This index provides the ratio between the in-plan area of earthquake resistant walls in each main direction (again, Y and X) and the total weight of the construction, reading:

$$\gamma 2,i = A_{wi} / G \qquad (2)$$

where, A_{wi} is the in-plan area of earthquake resistant walls in direction "i" and G is the quasi-permanent vertical action. This index is associated with the horizontal cross-section of the building, per unit of weight. Therefore, the height (i.e. the mass) of the building is taken into account; a major disadvantage is that the index is not nondimensional, meaning that it must be analyzed for fixed units. In cases of high seismicity, a minimum value of 1.2 m^2/MN seems to be recommended for historical masonry buildings (Meli 1998), but on the basis of a recent work (Lourenço & Roque 2004), a minimum value of 2.5 m^2/MN is adopted here for high seismicity zones.

2.3 *Base shear ratio*

The total design base shear for rigid structurs in a given direction shall be determined from the following relation (BNBC 1993):

$$V = 0.5ZIW \qquad (3)$$

where, Z and I are Seismic zone and Structure importance coefficient respectively. W (seismic dead load) is the total dead load of a building.

Finally, the base shear ratio provides a safety value with respect to the shear safety of the construction. The total base shear for seismic loading ($V_{Sd,\,base} = F_E$) can be estimated from an analysis with horizontal static loading equivalent to the seismic action ($F_E = \beta G$), where β is an equivalent seismic static coefficient related to the peak ground acceleration. The shear strength of the structure ($V_{Rd,\,base} = F_{Rd}$) can be estimated from the contribution of all earthquake resistant walls $F_{Rd,i} = \Sigma\ A_{wi}\ f_{vk}$, where, according to Eurocode 6 (CEN-EC6 2003), $f_{vk} = f_{vk0} + 0.4\sigma_d$. Here, f_{vk0} is the cohesion, which can be assumed equal to a low value or zero in the absence of more information, σ_d is the design value of the normal stress, and 0.4 represents the tangent of a constant friction angle φ, equal to 22º. The index, $\gamma 3$, reads:

$$\gamma 3,i = F_{Rd,i} / F_E \qquad (4)$$

If a zero cohesion is assumed ($f_{vk0} = 0$), $\gamma 3,i$ is independent from the building height, reading:

$$\gamma 3,i = V_{Rd,i} / V_{Sd} = A_{wi} / A_w \times \tan\varphi / \beta \qquad (5)$$

For a non-zero cohesion, which is most relevant for low height buildings, $\gamma 3,i$ reads:

$$\gamma 3,i = V_{Rd,I} / V_{Sd} = A_{wi}/A_w \times [\tan\varphi + f_{vk0}/(\gamma \times h)]/\beta \qquad (6)$$

where A_{wi} is the in-plan area of earthquake resistant walls in direction "i," A_w is the total in-plan area of earthquake resistant walls, h is the (average) height of the building, γ is the volumetric masonry weight, φ is the friction angle of masonry walls, and β is an equivalent static seismic coefficient. Here, it is assumed that the normal stress in the walls is only due to their self-weight, i.e. $\sigma_d = \gamma \times h$, which is on the safe side and is a very reasonable approximation for historical masonry buildings, usually made of very thick walls.

Equation (6) must be used rather carefully since the contribution of the cohesion can be very large. Within the scope of this work, a cohesion value of 0.05 N/mm^2 is assumed. This nondimensional index considers the seismicity of the zone, taken into account in β. The building will be safer with increasing ratio (earthquake resistant walls/weight), i.e. larger relation (A_{wi} / A_w) and lower heights. For this type of buildings and action, a minimum value of $\gamma3,i$ equal to one seems to be acceptable.

The adopted Indices measure rather different quantities and can hardly be compared. Index 2 is dimensional, which means that it should be used with particular care. Index 1 and index 2 are independent of the ground acceleration. Therefore, assuming that the buildings must have identical safety, these indexes should be larger with increasing seismicity. For indices 1 and 2, the seismicity is taken into account by considering that the threshold value, defined above, is valid for a PGA value of 0.25 g and assuming its linear variation with PGA/g, as illustrated in Figure 2 (a) and (b), see also Eurocode 8 (CEN-EC8 2003). On the other hand, index 3 should be constant in different seismic zones, as it intrinsically considers the effect of seismicity. This index format is close to the traditional safety approach adopted for structural design, being the threshold value equaled to 1.0; see Figure 2 (c). Even though, Proposed threshold values are plotted for Portugal, Spain, and Italian churches, in this paper, it is assumed that these threshold values to be equally applicable for identifing the vulnerable historical structures of Bangladesh.

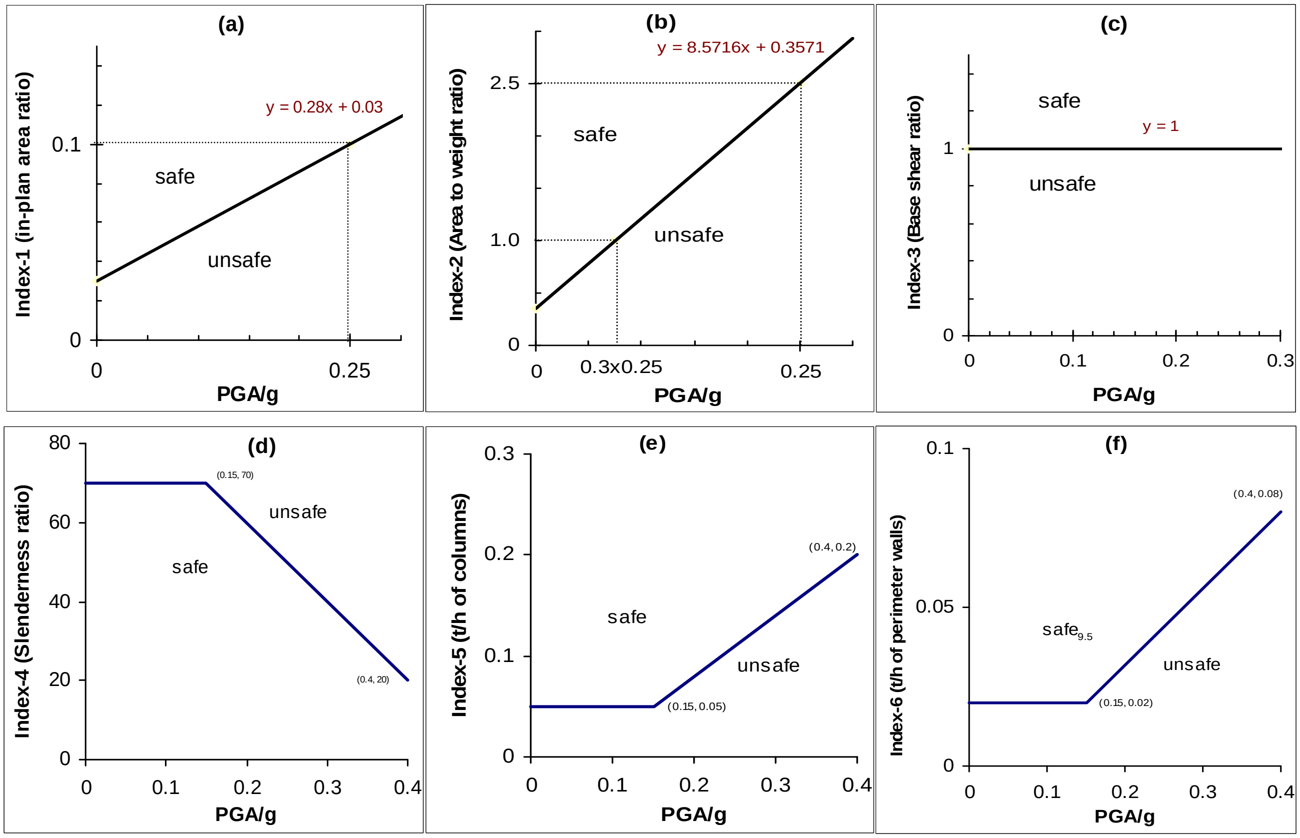

Figure 2. Assumed thresholds as functions of PGA/g: (a) index 1, (b) index 2, (c) index 3, (d) index 4, (e) index 5 and (f) index 6 (Laurenco & Oliviera 2004)

2.4 *Out-of-plane indices*

Besides the three Indices exposed above, other key Indices related to structural performance were computed for the monuments under analysis. In this study, three geometric ratios concerning the structural out-of-plane behaviour of columns and walls in main space were adopted, when applicable; slenderness ratio ($\gamma4$), and thickness to height ratio of the columns ($\gamma5$), as well as thickness to height ratio of the perimeter walls ($\gamma6$), were analyzed, reading:

$\gamma4 = h_{col} / (I/A)^{1/2}$ (7)
$\gamma5 = d_{col} / h_{col}$ or t_{col} / h_{col} (8)
$\gamma6 = t_{wal}l / h_{wall}$ (9)

where h_{col} is the free height of the columns, I and A are the inertia and the cross section area of the columns, respectively, d_{col} and t_{col} are the (equivalent) diameter and thickness of the columns, respectively, and t_{wall} and h_{wall} are the thickness and the (average) height of the perimeter walls, respectively. All of the out-of-plane Indices are dimensionless and do not consider the local seismicity. If identical safety factors for the monuments are assumed, these Indices should vary with increasing seismicity; namely, index 4 should decrease and indices 5 and 6 should increase. . For indices 4, 5 and 6, Assumed thresholds as functions of PGA/g are shown in Figure 2 (d), (e) and (f) respectively.

2.5 *Preliminary comparative analysis*

Eqs. 1, 2, 4 and 5 can be recast in a similar format as a function of the ratio (A_{wi} / A_w), which allows direct comparison between the different methods, as

Index 1: $\gamma1,i = A_{wi} / S = A_{wi} / A_w \,.\, A_w / S = A_{wi} / A_w \times k_1$ $[L^2/L^2]$
Index 2: $\gamma2,i = A_{wi} / G = A_{wi} / A_w \,.\, 1 / (\gamma \times h) = A_{wi} / A_w \times k_2$ $[L^2/F]$
Index 3: $\gamma3,i = V_{Rd,\,i} / V_{Sd} = A_{wi} / A_w \,.\, \tan\varphi / \beta = A_{wi} / A_w \times k_3$ $[F/F]$
$k_1 = A_w / S$; $k_2 = 1 / (\gamma \times h)$; $k_3 = \tan\varphi / \beta$

Here, it is stressed that the ratio (A_{wi} / A_w) represents the percentage of earthquake resistant walls in a given direction in relation to the total area of earthquake resistant walls in the building.

The new expressions for the scalar Indices indicate that they are all linearly dependent on the ratio (A_{wi} / A_w). This ratio provides direct information about the in-plan stiffness of the structure along each main direction and it is usually accepted that the sum of the relations (A_{wi} / A_w) for the two orthogonal directions can be larger than the unit value, due to superposition of the areas in the two directions.

The Indices depend linearly also in the following quantities: (a) ratio between total area of earthquake resistant walls and total in-plan area of the building (Index 1); (b) height of the building (Index 2); (c) ratio between friction and equivalent seismic static coefficient (Index 3). This stresses the fact that the Indices measure rather different quantities and can hardly be compared between them. Index 2 is dimensional, which means that it should be used with particular care. Index 1 and Index 2 are independent of the design ground acceleration. Therefore, assuming that the buildings must have identical safety, these Indices should be larger with increasing seismicity. On the other hand, Index 3 should be constant in different seismic zones, as it considers the effect of seismicity. Finally, Index 3 format is close to the traditional safety approach adopted for structural design.

3 SEISMIC HAZARD ZONATION OF BANGLADESH

The seismic map of Bangladesh is provided in Figure 48 Based on the severity of the probable intensity of seismic ground motion and damages; Bangladesh has been divided into three zones, i.e. Zone 1 (Zone factor = 0.25), Zone 2 (Zone factor = 0.25) and Zone 3 (Zone factor = 0.25) as shown in Figure 48 with Zone 3 being the most severe (BNBC 1993) (see Figure 3). The proposed geometrical indices of monuments located in different seismic areas are compared with the respective seismic hazard, expressed by the peak ground acceleration (PGA). PGA for 0.002, 0.001 and 0.0004 annual probability of exceedence are picked and used to plot the Seismic hazard map (PGA contour) of Bangladesh for ten percent, five percent and two percent probability of exceedence in 50-years period respectively (Yasin 2008). The map developed using Boore et al. (1993), McGuire (1978) and Duggal (1989) acceleration attenuation expressions (Yasin 2008) (see Figures 4, 5, 6).

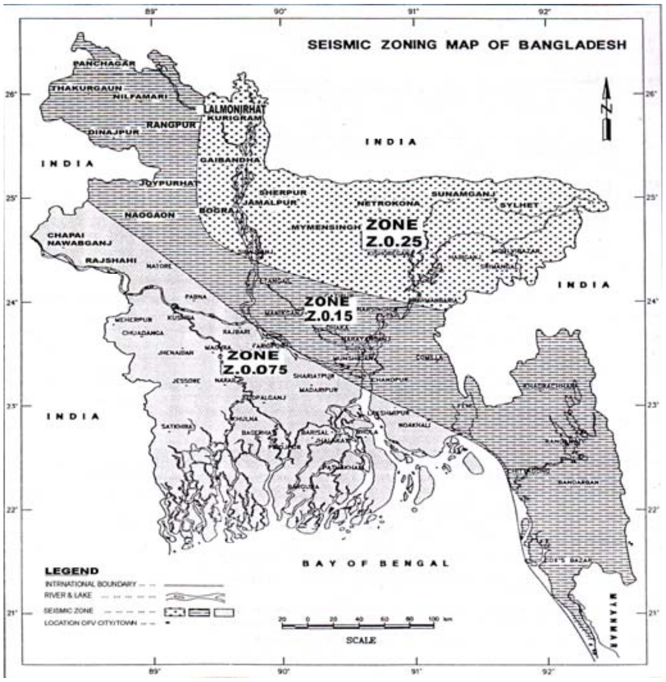

Figure 3. Seismic Zoning Map of Bangladesh (BNBC 1993)

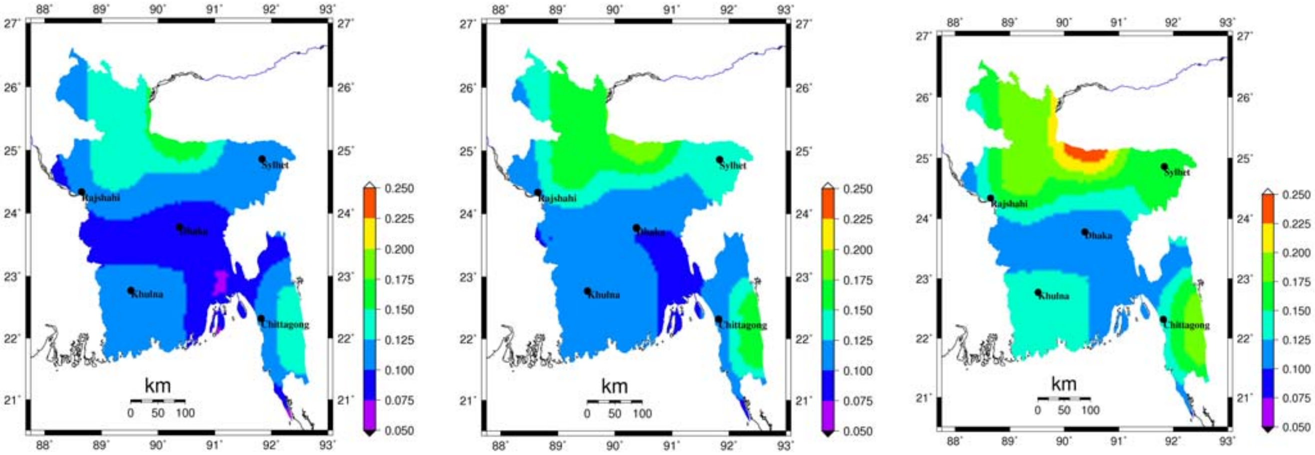

Figure 4. Seismic hazard map of Bangladesh based on (a) ten, (b) five, (c) two percent probability of exceedence in 50-years period (using Boore et al. (1993) acceleration attenuation expression), contour values are PGA in g

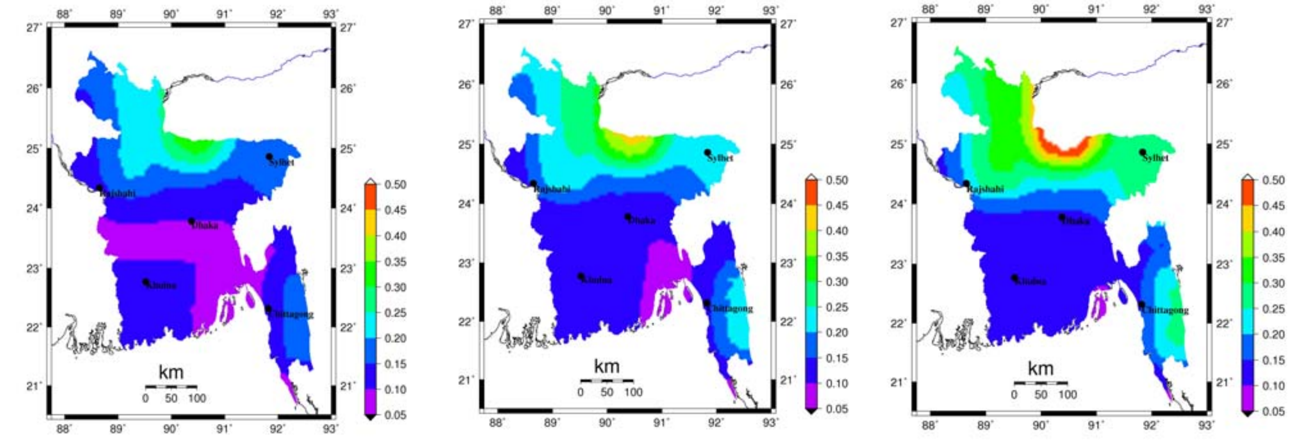

Figure 5. Seismic hazard map of Bangladesh based on (a) ten, (b) five and (c) two percent probability of exceedence in 50-years period (using McGuire (1978) acceleration attenuation expression), contour values are PGA in g

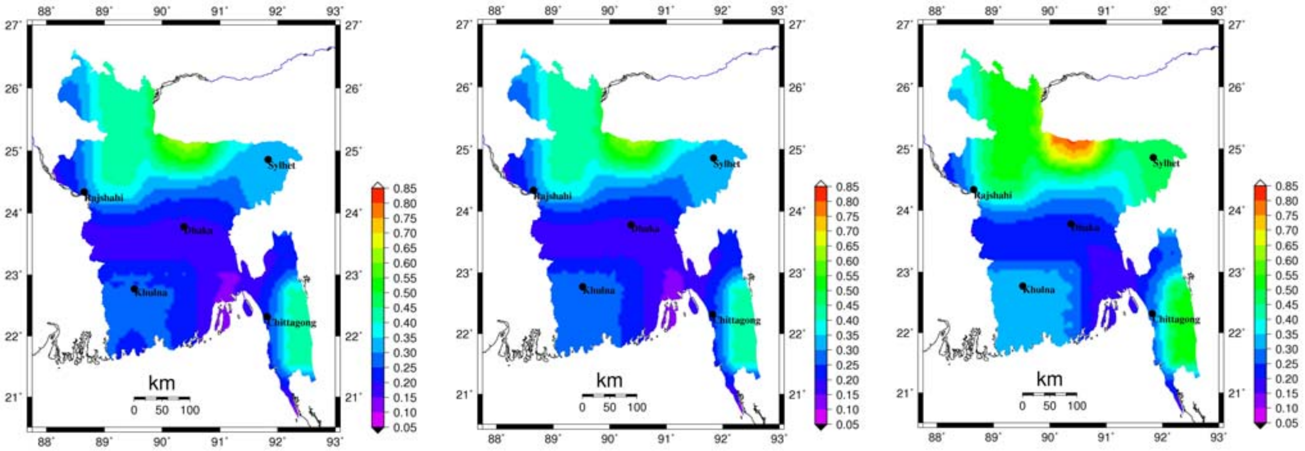

Figure 6. Seismic hazard map of Bangladesh based on (a) ten, (b) five and (c) two percent probability of exceedence in 50-years period (using Duggal (1989) acceleration attenuation expression), contour values are PGA in g

4 DESCRIPTION OF SELECTED MOSQUES

In this paper, Twenty-eight historical masonry mosques have been selected which are located in different districts of Bangladesh, built between 13th to 18th centuries. The following article a detailed description of Choto Sona Mosque is given and for other mosques a short description are provided in tabular form.

4.1 *Chhota Sona Mosque*

Chhota Sona Mosque sometimes described as a 'gem of Sultanate architecture (1493 -1519 A.D.)' is situated in the western most part of Bangladesh in the district of Chapainawabganj, only 2 km inside from the border with India. The mosque is one of the best-preserved Sultanate monuments under the protection of the Department of Archaeology and Museums, Government of Bangladesh (GoB). The mosque was built by one Wali Muhammad during the reign of Sultan Husayn Shah.

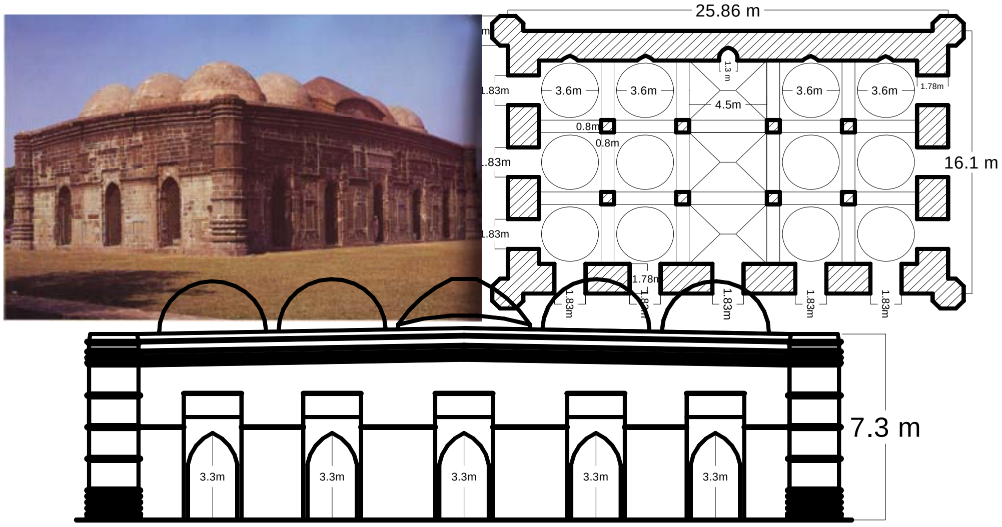

Figure 7. Photo, Plan and Elevation of Sona mosque.

The Chhoto Sona mosque is an isolated building from its present neighbourhood and stands on an open piece of land in the southern side of a big tank. The area of the mosque was enclosed with a boundary wall which does no longer exist. At a little distance from the gate stand two tombs. H. Creighton suggests that the tombs belong to the founder of the mosque and one of his kindred (Creighton 1871: XIV). On the south-eastern side of the courtyard is the new grave of Bir Shresto Mohiuddin Jahangir buried in 1971 during the Liberation War.

The mosque is a small building of great architectural merit in a seemingly good state of preservation. A part of the western wall along with three domes fell during the Great Indian earthquake in 1897 and subsequently it was restored in 1900-07 by the Archaeological Department of India (Annual Report ASI 1908-09: 45). It has only one prayer hall with simple rectangular floor plan measuring 22.30x12.54 m from the inside. The hall is divided into three bays and five aisles. The middle aisle is broader and divides the prayer chamber in two parts. Each part consists of six quadrilateral areas covered by six semicircular domes. The central nave is divided into three rectangular areas covered with three special forms of vaults called Chouchala. The prayer room is surrounded by a 1.78 m thick wall with eleven pointed multi-foil arched openings. Photo, plan and front elevation of the mosque are shown in Figure 7.

Figure 8. Map of Bangladesh showing the location of selected mosques

4.2 *Other mosques*

Figure 8 shows the map of Bangladesh gives the location of all the mosques sites covered in this study numerically. And Table1 presents short description of those historical mosques.

Table 1. Other mosques.

Sl. No.	Name of Mosque	Age in Years	Location	Sizes
1	Chhoto Sona Mosque	200 to 400	Chapainawabganj	25.86mX16.1m
2	Ghorar Mosque		Barobazar, Jhenidah	9mX12.53m
3	Jore Bangla Mosque		Barobazar, Jhenidah	9.37mX9.37m
4	Golakata Mosque		Barobazar, Jhenidah	11.83mX8.22m
5	Shait Gambuj Mosque		Bagerhat	48.95mX32.25m
6	Noy Gambuj Mosque		Bagerhat	17mX17m
7	Chunakhola Mosque		Bagerhat	7.64mX7.64m
8	Ronbijoypur Mosque		Bagerhat	16.4mX16.4m
9	Baba Adam Mosque		Rampal, Munshiganj	13.93mX10.34m
10	Rajbibi Mosque		Chapainawabganj	13.05mX17.82m
11	Dhunichak Mosque		Chapainawabganj	17.28mX12.66m
12	Goaldi Mosque		Goaldi, Sonargaon, N.ganj	8.08mX8.08m

13	Bagha Mosque		Rajshahi	26.35mX12.86m
14	Sura Mosque		Dinajpur	8.53mX12.18m
15	Kherua Mosque		Sherpur, Bogra	17.5mX7.54m
16	Atiya Mosque		Tangail	10.52mX16.51m
17	Shah Muhammad Mosque		Pakundia, Kishoreganj	9.14mX9.14m
18	Shah Niamatullah Mosque		Chapainawabganj	19.81mX7.62m
19	Khawaja Shahbaz Mosque		Doyel Chattar, Dhaka	20.73mX7.92m
20	Sat Gambuj Mosque		Mohammadpur, Dhaka	17.67mX8.22m
21	Lalbag Fort Mosque		Lalbag Fort, Dhaka	19.5mX8.22m
22	Khan M Mridha Mosque		Lalbag, Dhaka	14.63mX7.31m
23	Miah Bari Mosque		Karapur, Barisal	13.49mX6.1m
24	Bazra Mosque		Begumganj, Noakhali	15.77mX7.54m
25	Dewanbari Mosque		Aminbazar, Dhaka	7.42mX8.01m
26	Karzon Hall Musa Mosque		Dhaka University, Dhaka	15.17mX7.54m
27	Bibir Mosque		Lalmatia, Dhaka	18.7mX11.7m
28	Aambour Shah Shahi Mosque		Kawranbazar, Dhaka	13.41mX7.3m

5 RESULTS AND DISCUSSION

For the application of the simplified analysis methods, it was assumed that all the masonry materials were similar; the volumetric weight of masonry was 18 kN/m3. The values computed for the three in-plane indices and three out-of-plane indices are graphically represented in Figures 10 and 11 along X and Y directions respectively, for the entire sample, as a function of the local parameter PGA/g. the peak ground acceleration was estimated for 0.002, 0.001 and 0.0004 annual probability of exceedence and in order to BNBC (see Figures 3, 4, 5 and 6). Figure 9 shows using legend in Figures 10 and 11.

In terms of average values, all in-plan indices present lower values in the transversal direction (Y) than longitudinal direction (X). In out-of- plane indices can be observed that maxima index-4 values (column's slenderness) tend to decrease with increasing seismicity and that both minima index-5 and index-6 values seem to increase continuously with seismicity. When a comparison is made using the proposed threshold, No indexes are exceeded almost all mosques in longitudinal direction.

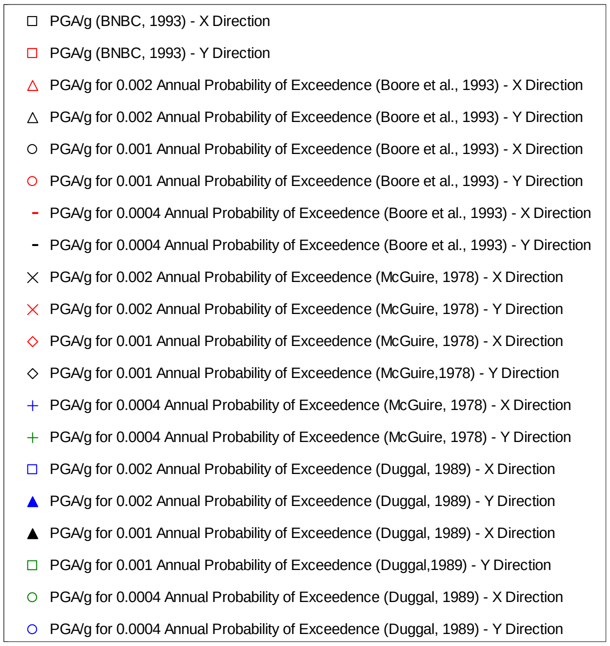

Figure 9. Using Legend

In terms of average values along Y-axes, Chhoto sona mosque, Shait Gambuj mosque, Bagha mosque, Kherua mosque, Shah niamatulla mosque, Khawaja shahbaz mosque and Lalbag fort mosque are exceeded Index-2 and -3 thresholds in only Y-direction when the design peak ground acceleration above 0.15g. For the higher seismicity (design ground acceleration above 0.25 g), Noy Gambuj mosque is exceeded Index-2 threshold line. About 67.86% of sample, No in-plan indices exceed it in both direction. The value of base shear ratio (γ3) and three out-of- plane indices are sufficient almost all mosques in transversal direction (Y). Table 1 presents the eight monuments of the sample that exceed at least one index in one direction.

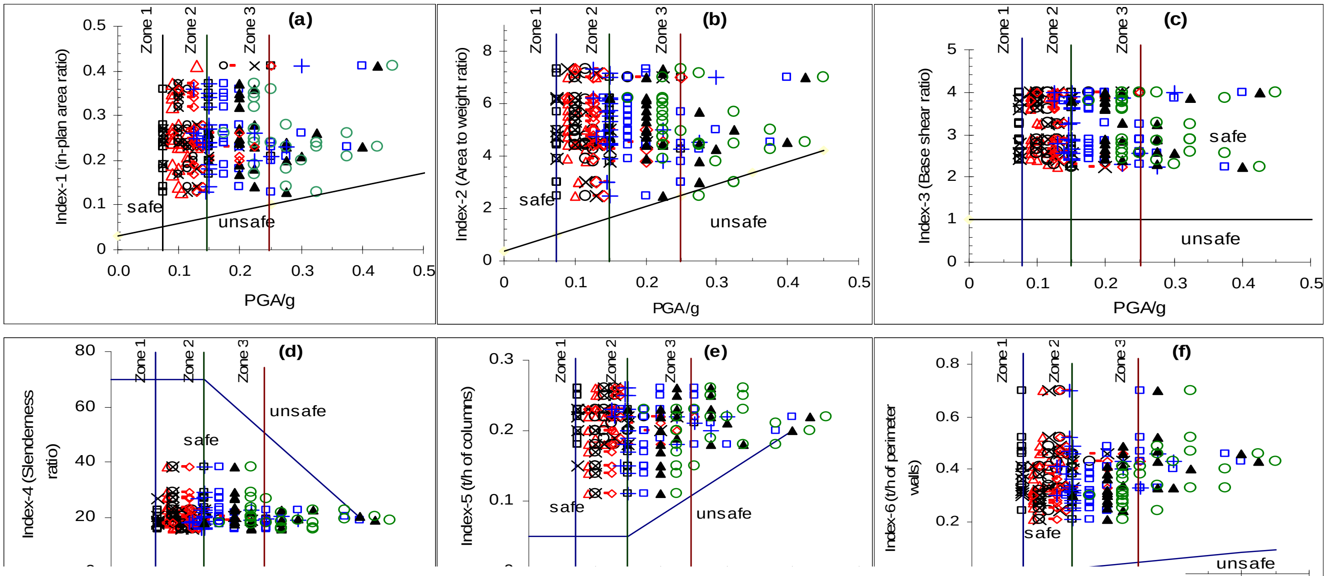

Figure 10. Relationship between Indices ((a) In-plane area ratio, (b) Area to weight ratio, (c) Base shear ratio, (d) Slenderness ratio, (e) t/h of columns, (f) t/h of perimeter wall), and PGA/g along X-axes for the entire sample.

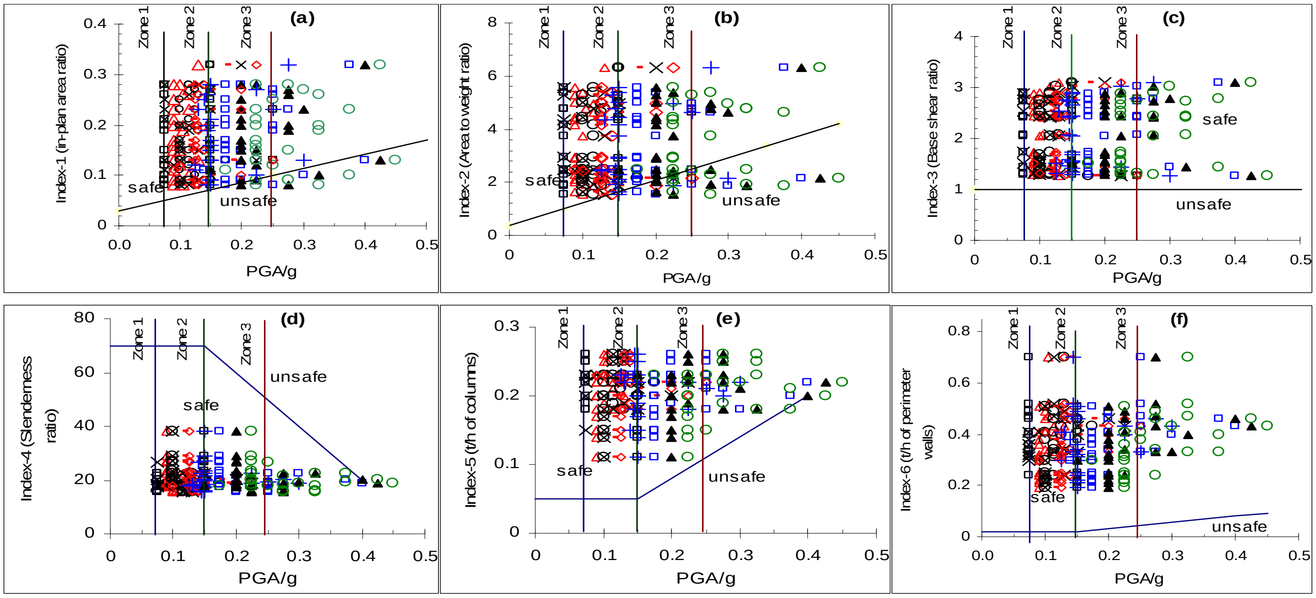

Figure 11. Relationship between Indices ((a) In-plane area ratio, (b) Area to weight ratio, (c) Base shear ratio, (d) Slenderness ratio, (e) t/h of columns, (f) t/h of perimeter wall) and PGA/g along Y-axes the entire sample.

Table 2. Monuments in which are exceeded at least one index in one direction.

Monuments	Index / Direction / PGA	Monuments	Index / Direction / PGA
Chhoto sona mosque	Index 1 / Y / above 0.2g Index 2 / Y / above 0.15g	Kherua mosque	Index 1 / Y / above 0.35g Index 2 / Y / above 0.2g
Shait Gambuj mosque	Index 1 / Y / above 0.2g Index 2 / Y / above 0.2g	Shah niamatulla mosque	Index 1 / Y / above 0.2g Index 2 / Y / above 0.25g
Noy Gambuj mosque	Index 2 / Y / above 0.25g	Khawaja shahbaz mosque	Index 1 / Y / above 0.2g Index 2 / Y / above 0.2g
Bagha mosque	Index 1 / Y / above 0.25g Index 2 / Y / above 0.15g	Lalbag fort mosque	Index 1 / Y / above 0.17g Index 2 / Y / above 0.15g

6 CONCLUSIONS

This study presents an investigation about the possibility of using simplified methods of analysis and simple indices as indicators for fast screening and decision to prioritize deeper studies in historical masonry buildings and assess vulnerability to seismic actions. Even though, Lourenco and Oliveira used thresholds as functions of PGA/g to analyze historical masonry structures by this method for evaluating seismic vulnerability of churches (Lourenco & Oliveira 2004). In this paper, it is assumed that these threshold values to be equally applicable for identifying the vulnerable historical masonry structures of Bangladesh. These indices are based mostly on the in plan dimensions and height of the buildings.

The usage of simplified methods was made, taking into consideration the in-plan area of the building, its height and seismicity, with the simultaneous verification of two indices, one related to ratio of in plan area ($\gamma 1$) and weight ($\gamma 2$), and another related to the maximum base shear force ($\gamma 3$). The analysis of the out-of-plane indices shows that a logical common trend can be established. In general, the longitudinal direction of the buildings (X) exhibits much lower vulnerability than the transversal direction (Y). In terms of average values, the results show that almost all mosques are safe except eight (28.58%) mosques of the samples. For the high seismicity, these eight mosques are vulnerable in the short or Y-direction only and required careful attention and deeper investigation at risk.

REFERENCES

Annual report of the Archaeological Survey of India, Eastern circle, Calcutta 1908-09

CEN, 2003. "Eurocode 8: Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings", prEN 1998-1 (Final Draft), Comité Européen de Normalisation, Brussels, Belgium.

CEN, 2003. Eurocode 6: Design of masonry structures, prEN 1996-1, Brussels.

Giuffrè, A. 1995. Seismic damage in historic town centers and attenuation criteria, Annali di Geofisica, 38(5–6), 837–843.

ICOMOS, 2001. Recommendations for the analysis, conservation and structural restoration of architectural heritage.

Cunningham, A. Report of a Tour in Bihar and Bengal in 1879-80, Calcutta 1882.

Lourenço, P. & Roque, J. 2004. Simplified indexes for the seismic vulnerability of ancient masonry buildings, Construction and Building Materials (submitted).

Lourenco, P. B. & Oliveira, D. V. 2004. Seismic vulnerability of historical churches, Proceedings of International Workshop on Masonry Walls and Earthquakes.

Meli, R. 1998. Structural engineering of historical buildings (in Spanish), Mexico-City, Fundación ICA.

Noor, M. A., Yasin, M. & Ansary, M. A. 2005. Seismic Hazard Analysis of Bangladesh, Proceedings of First Bangladesh Earthquake Symposium, Dhaka, Dec.14-15, 2005.

Yasin, M.Sc. Engg. Thesis (2008). Seismic Performance Assessment of Reinforced Concrete Frame Structures.