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Seismic Behavior of Historic Masonry Monasteries in Sikkim in the 2011 M 6.9 Sikkim Earthquake: Case Study of Hee Gyathang Monastery, North Sikkim, India

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Abstract

The Himalayan region is, one of the most seismically vulnerable and tectonically active zones in the world. Sikkim is a state in North-East India, situated on the Himalayan arc. Sikkim is dotted with numerous Buddhist monasteries dating back to the 17th century. These historical monastery structures are a part of the rich cultural heritage of the state, being structures of social, cultural and religious significance to the community. The old monasteries are typically load bearing structures where stone masonry and timber are used extensively as columns, beams, floors, roofs and also in staircases. The monasteries follow some spatial characteristics such as regular geometrical shapes in plan with an assembly hall and front verandah, and are usually one or two storeys high with diminishing upper storeys topped by light weight sloped roofs. The M6.9 earthquake on September 18, 2011, in Sikkim has clearly demonstrated the vulnerability of the historical monastery structures. The evaluation of the earthquake vulnerability of monasteries is a necessary first step for their protection in future earthquakes. This paper analyzes the performance of one of the non-engineered monastery structure made with load bearing stone masonry - the century old hilltop Hee Gyathang Monastery located in the North District about 30 kms from Mangan. Structural analysis by demand capacity method of this monastery proves that the monastery is unsafe after the 2011 M 6.9 Sikkim Earthquake.

Keywords: Sikkim earthquake; Monastery; Structural analysis; Demand capacity method

Introduction

Sikkim is a state in North-East India, situated on the Himalayan arc that is made up of a number of parallel fault systems, namely, Himalayan Frontal Fault (HFF), Main Boundary Thrust (MBT), Main Central Thrust (MCT), Trans Himalayan Fault and the Indus-Tsangpo Suture [1]. In the Sikkim Himalayas, the MBT and MCT are not parallel which has been reported as a major controlling factor for earthquakes that has made the entire state highly earthquake prone [2]. Sikkim has about 250 Buddhist monasteries, the oldest dating back to the seventeenth century. The monasteries are made with load bearing stone masonry along with timber frame. An earthquake of magnitude 6.9 occurred on 18th September at 18:11 hrs IST in Sikkim-Nepal Border region. The preliminary hypo-central parameters of this earthquake, as estimated by the Seismic Monitoring Network of India Meteorological Department (IMD) are given in Table 1. This region the monasteries are situated in hilly terrain not far from the China-Tibet border. The monasteries located in this area experienced extensive damages during this earthquake. Hee Gyathang Monastery was built in 1914 and is representative of the architectural and structural typology mentioned earlier. The monastery caters to the devotional needs of the Nyingmapa Sect of Buddhism. This remotely located monastery is rich in architectural value and is of special significance to devotees, adding to its socio cultural value for the community.

Location/Accessibility of Hee Gyathang

Monastery The Hee Gyathang Monastery (Figure 1) is situated in a solitary hill top location. The nearest settlement is Hee Gyathang village

Figure 1: Hee Gyathang Monastery.

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Date of occurrence	18/09/2011
Time	18 11 hrs (IST)
Magnitude	6.8
Focal depth	10 Km
Epicentre	Latitude and Longitude 27.70° N and 88.20° E
Region	Sikkim-Nepal Border region.

Source: http://www.imd.gov.in/section/nhac/dynamic/eq.pdf. (last accessed 19.9.16)

Table 1: Data on 2011 Sikkim Earthquake.

on the road from MangantoGor via Sankalan. The monastery is located 2.5 kms from the village and can be accessed only on foot through an arduous one hour hike through a steep pathway through dense forests, without any human habitation along the way (Figure 2). The monasteryis built on a small patch of flat ground about 1600 sqm area on a hill top at an altitude of 1669 meter (Figure 3). The geographical coordinates are simultaneously 27.4750 N and 088.5010 E.

Planning and Site Consideration

The old two storied load bearing monastery structure sits on a 500 mm high plinth amidst soft landscape.The ground floor has an assembly hall (8.7 m × 10.35 m) with an altar of 775 mm width at its rear end. The ground and first floors have the same plan footprint (Figures 4-6). Presently, the statues have been shifted to the new monastery while the old one lies abandoned. Both the floors have similar fenestration with two windows located on the northern and southern walls. The front of the monastery has a wooden verandah of 900 mm width (Figure 7). The fenestration pattern on the rear side is not the same on both the floors. While the first floor has two window openings, the ground floor has none (Figure 8). It is noticed that the old windows have been replaced by new ones (Figure 9).
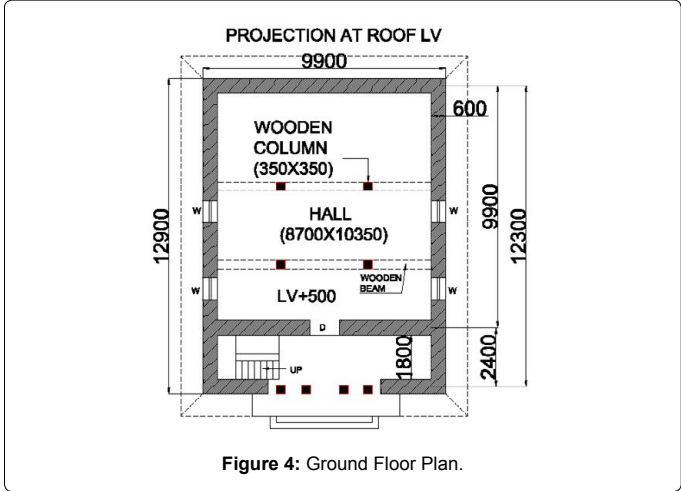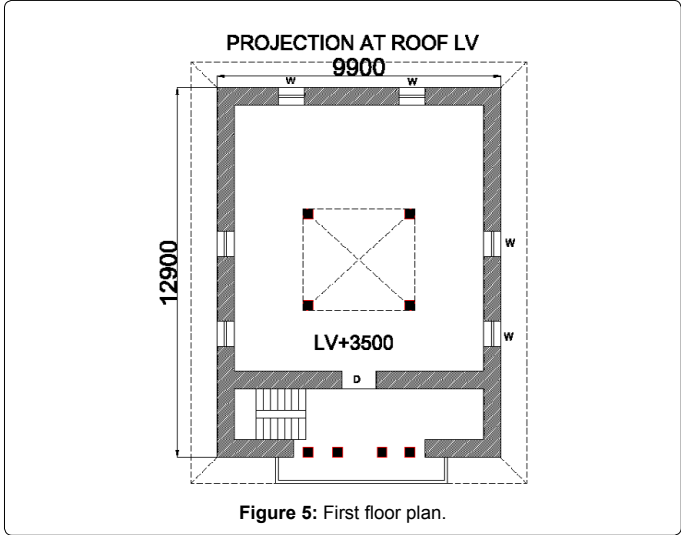

Figure 2: Beginning of the path from the motorable road.
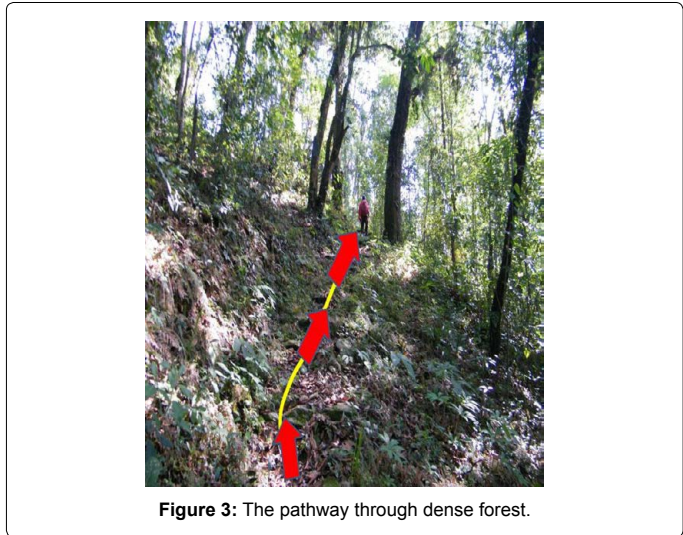
Figure 3: The pathway through dense forest.

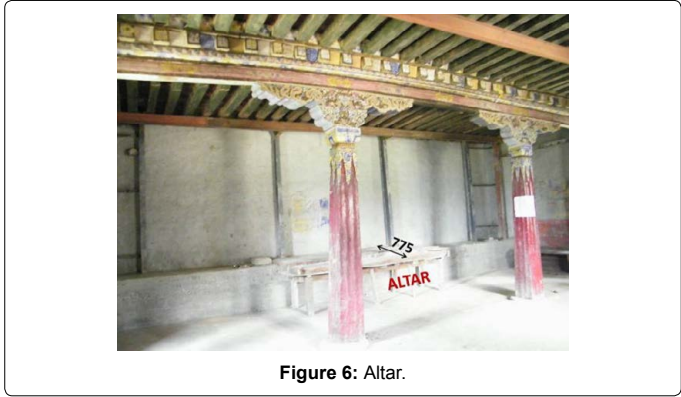**Figure 4:** Ground Floor Plan.

Figure 5: First floor plan.

Figure 6: Altar.

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Structural System

The old monastery is made with Random Rubble stone masonry structure (Figure 10) with a thickness of 600 mm. Four timber posts are located at the centre of the assembly hall, only two horizontal beams are observed above the wooden posts spanning only in the "X" direction (Figure 11).The wooden posts are decorated at the top (Figure 12). Two decorated wooden posts are located at the entrance of the front verandah (Figure 13). No bands are present in the monastery. Floors

Figure 10: Rubble masonry.

Figure 7: Projected Covered Wooden Verandah.

Figure 11: Wooden columns and beams inside the Hall.

Figure 8: Back side wall.

Figure 12: Timber Column.

Figure 9: Window.

Figure 13: Timber Columns infront of Verandah.

are made with timber planks. Wooden rafters hold the timber plank in the first floor (Figure 14). Roof is covered with G.I sheets (Figure 15).

Seismic Load Analysis

The Demand Capacity Ratio (DCR) method is an useful tool to determine the capacity of a building to resist seismic action, through

Figure 14: Wooden Rafter and Planks.

Figure 15: Roof.

determination of the seismic demand and the calculation of the ratio of demand vis a vis capacity [3]. DCR values less than or equal to one indicate that a structure is safe. DCR values in excess of one indicate that a structure is unsafe since the structural capacities are less than the seismic demand imposed on the building. The combined stress due to direct axial compression and stress is given by expression $P/A \pm M/Z$ where,

P=Axial compressive force on the determined wall

A=area of the wall under consideration.

M=Moment at the base of wall.

Z=Section modulus=$I/y = bd3/12 \div d/2 = bd2/6$ [where, b=Breath, d=Depth].

I=Moment of Inertia.

A negative value for the above expression indicates that the structure will be unsafe, that is, the masonry wall is subjected to tensile stress, which it is inherently incapable of resisting.

DCR Computations were done for shear stress, tensile stress and overturning.

For shear stress, DCR=$V_{avg}, I/fs$

For Tensile stress, DCR=$\sigma t/c, i/fb$

For Overturning, FOS=Ms/MO

Where,

Bending stress=σ_{bi}

Direct Axial Stress=σ_{di}

Average Shear stress=$V_{avg}, I = Qi/Awall$

fs=The permissible shear stress calculated on the area of bed joint shall be in accordance with clause 5.4.3 of IS:1905-1987

Ms=Stabilizing moment due to dead load at bottom of the wall

M0=Total moment of the bottom wall

Overturning Moment=FOS=Ms/Mo

The design parameters were taken from IS 1893:2002.

The entire state of Sikkim lies in Zone IV with maximum expected intensities of VIII on the Modified Mercalli Intensity (MMI) scale. As per IS 1893:2002 (Part 1) the Zone Factor Z is 0.24 for seismic zone IV. The value of Importance Factor, I is chosen 1.2 for being religious building. For unreinforced load bearing masonry wall building has the Response Reduction Factor, R is 3 [4-6]. During earthquake shaking a building will oscillate to and fro in any mutually perpendicular directions. The Fundamental Natural Period (time taken to complete one back and forth motion in seconds), derived from the expression $Ta=0.09h/\sqrt{d}$ (IS 1893:2002), where, h=Height of building, in metres, d=Base dimension of the building at the plinth level, in m, along the considered direction of the lateral force. (To get the lesser value of 'T' the longer dimension of the base is considered.) Sa/g=Spectral Acceleration Co-efficient (As per the graph for Rocky and hard soil considering 5% damping the value of Sa/g is 2.5.) (Figure 16 and Tables 2-6) [7-9].

Findings and Concluding Remarks

After the 2011 earthquake, it was observed that the old structure had suffered edirreparable damages. Visual inspection revealed the deteriorated condition of the monastery due to these damages (Figures 17-19). The random rubble masonry walls suffered bulging due to out of plane bending (Figure 20), diagonal and plaster cracks developed on the inside walls plaster (Figure 21) The timber posts also suffered bending (Figure 22). The damages sustained may be attributed to the inability of the walls to withstand the tensile stresses generated during earthquake induced shaking. Clearly, these cracks have weakened the structure and remedial measures need to be taken to prevent their further propagation. However, it is noteworthy that the structure has not collapsed despite suffering such widespread damage. The DCR values indicate that the structure should have sustained Grade
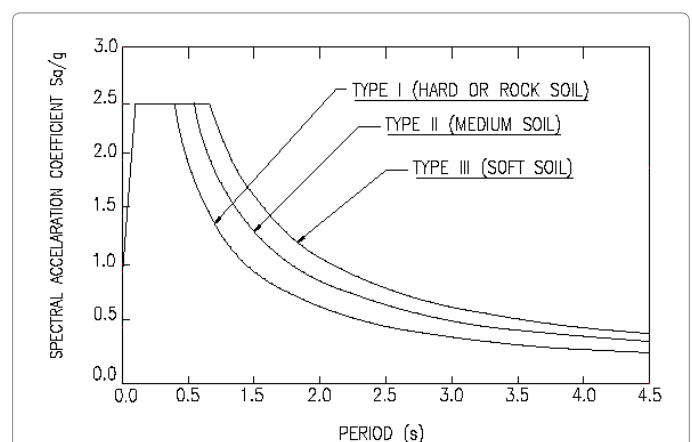

Figure 16: Response Spectra for Rock & Soil Sites For 5% Damping [9]. Ah: Design Horizontal Spectrum Value: W: Seismic wt of all floors of the building (Dead load and part of the imposed load - IS 1893-2002). VB: Seismic Base Shear is the total design lateral force on the building at the base of the structure. It is directly proportionate to the weight of the building.

SEISMIC WEIGHTS=W (KN)			
W_1(Ground Floor)	2205KN	Zone Factor=(Z)=0.24	Design horizontal spectrum value=A_h=0.12
W_2(First Floor)	1890KN	Importance Factors=(I)=1.2	Seismic weights (W)=4740KN
Dead load (DL)	478.9KN	Response Reduction Factor=(R)=3	$V_B=A_h \times \sum W$=711KN
Live Load (LL)=	63.9KN	Spectral Acceleration Co – efficient=(Sa/g)=2.5	
Dead load of flexible roof=	100KN	A_h=Z/2 x I/R x S_a/g=0.12	
Total weight of the structure (W)	4740KN		

NOTE: This design horizontal seismic coefficient A_h is determined by the following expression provided that for any structure with T ≤ 0.1 Sec the value of A_h will not be taken less than Z/2 whatever the value of I/R.
Sa/g=Spectral Acceleration Co – efficient depends on i) Fundamental Natural Period 'T' and ii) the type of soil at the site. Soil type of Sikkim is Hard Rock.
The Sa/g value can be derived from the graph (Figure 16) - Response Spectra for Rocky Soil Sites For 5% Damping.

Table 2: Design shear calculation. Wi: seismic weight of floor, hi: height of floor I measured from base, n: number of storeys in the building, Vavg,I: The average shear stress of a building at any level, Qi: storey shear or designed lateral force at floor (i) at the level under consideration determined, Aw: 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.

Story Level	Wi (KN)	h_i(m)	$W_ih_i^2$ (KN m²)	$Wihi2 \sum Wihi2$	$Q = VBX\,Wihi2 \sum Wihi2$	
					X Direction (KN)	Y Direction (KN)
Ground	Wi_1=2747.7	3.5	33660.1	0.286	Q_1=203.3	203.3
First	Wi_2=1990	6.5	84077.5	0.714	Q_2=507.7	507.7
			11773.76	1	711	711

Table 3: Lateral load distribution with height by the static method.

For Flexible Diaphragm			
Q_1	=203.3 KN	Q_2	=507.7 KN
V_{max}	=67.8 KN/m	V_{min}=	=41.3 KN/m
Moment causes due to V_2 (Figure 20)	=355.81KNm	Moment causes due to V_{max} at bottom of the wall (Figure 19)	=1651.0 KNm

Total moment of bottom wall=(M_0)=(1651.0 +355.81) KNm=2006.81KNm (Figure 19)

Table 4: Lateral Load Distribution for flexible diaphragm.

Moment of Inertia=I	bd³/12	40.218 m⁴
Bending stress=σb.i	M_0/I * Y	232.03KN/m
Direct Axial Stress=σd,i	$\sigma_{d,i}$=P/A	130KN/m²
Direct and Bending stress=σt/$_{c,i}$	σt/$_{c,i}$=$\sigma_{d,i} \pm \sigma_{b,I}$	+ 362.03KN/m² and -102.03KN/m²
Average Shear stress at the Bottom of the Wall=$V_{avg,I}$	Q/A_{wall}	63.74KN/m²
Over turning Moment	FOS=M_s/M_0	1.68

Table 5: The combined stress due to direct axial compression.

|	Permissible stresses	Actual stresses	DCR	Remarks
Shear Stress	f_s=0.22	$V_{avg,I}$=0.06374	V_{avg}/f_s=0.29	This DCR value is within the allowable limit which indicates the structure safe under shear stress.
Compressive Stress	f_b=0.87	σt/$_{c,I}$=0.36203	σt/$_{c,I}$/f_b=0.416	The structure is safe in Compressive stress as the DCR value is less than unity
Tensile stress	f_t=0.05	σt/$_{c,I}$=0.10203	σt/$_{t,I}$/f_t=2.04	This value (2.04) is greater than unity indicates that the masonry structure is under tension beyond its allowable value.
Over turning			1.5/FOS=0.89	The structure is safe in Overturning as the DCR value is less than unity

Table 6: Computation of DCR.
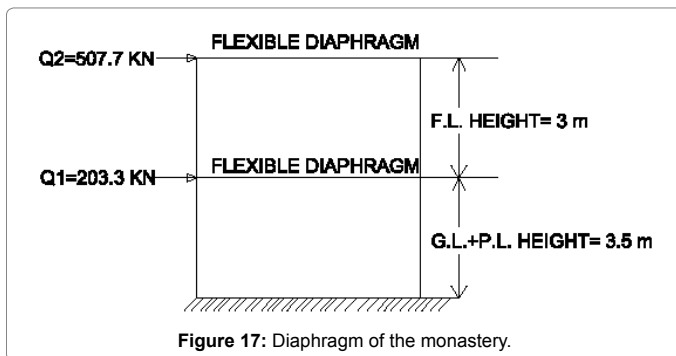
Figure 17: Diaphragm of the monastery.

Figure 18: Distribution of Lateral loads (Plan View).

1 damage as per IS 1893: 2002, that is, fine cracks in plaster. However, the structure experienced moderate and heavy damage including small, large and deep cracks in plaster, bulging of columns, gaps in
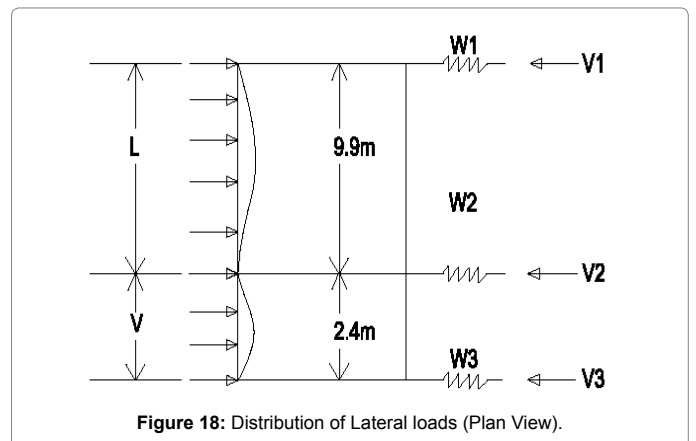
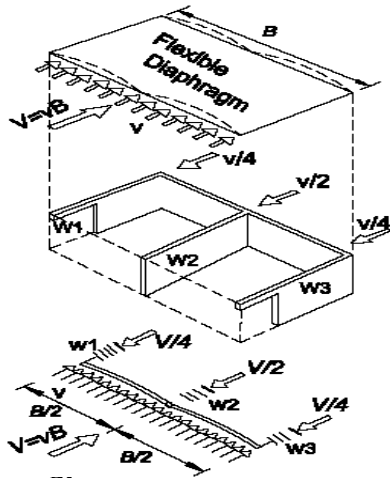**Figure 19:** Distribution of Lateral loads (3D View).

Figure 20: Shear cracks and bulging of wall in bending.

Figure 21: Plaster cracks.

Figure 22: Bulging in columns.

in the earthquake prone state Sikkim. It is not too late to evaluate the earthquake vulnerability to all old historic monasteries and suggest a way forward for their protection and preservation.

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walls and loss of cohesion in parts of the building indicating that the actual damage level sustained was Grade 3 as per Is Code 1893: 2002. So this analysis has pointed out that the historical monasteries have become vulnerable and are in jeopardy. So far very little work has been done to formally assess the vulnerability of the historical structures