CENTER FOR DISASTER RISK REDUCTION AND COMMUNITY DEVELOPMENT STUDIES (CDRR&CDS)

Seismic Vulnerability of Bhutanese Vernacular Buildings

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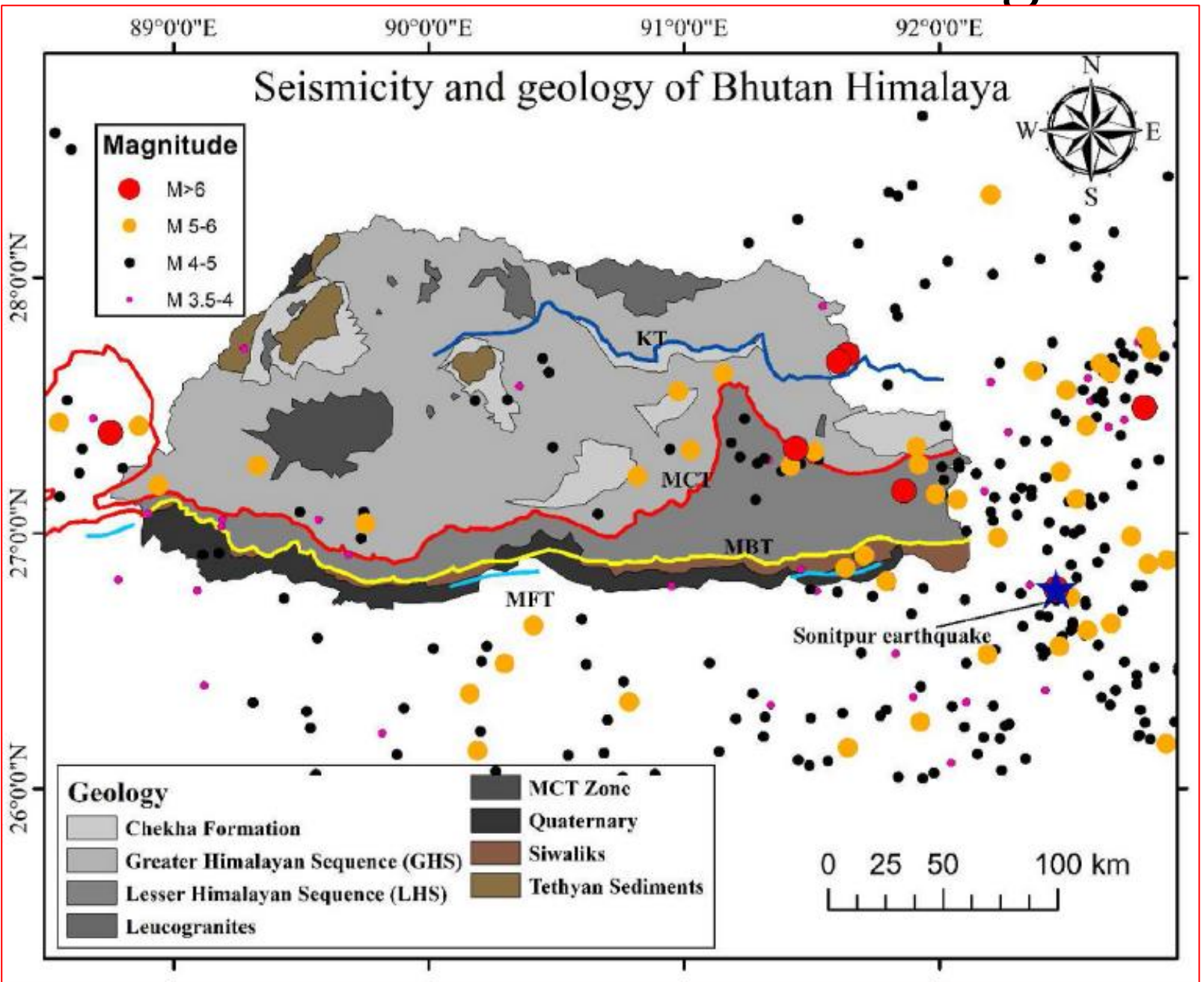
Overview of Presentation

1. Geological settings of Bhutan
2. From history to hitherto: *Timeline and tales of earthquakes in Bhutan*
3. Taxonomy of Bhutanese Buildings
4. Seismic Vulnerability of Vernacular Residential Buildings in Bhutan
5. Key observations on damages
6. Learning from the past: Damages and lessons from historical earthquakes in Bhutan
7. Insights : ongoing research in CST

Geo-seismo-tectonic setting of Bhutan Himalaya



- **Fig:** Seismicity and geology of Bhutan Himalaya (modified and updated from [Long et. al]).
- Four tectonic sections as the Tethyan Sedimentary Series (TSS), Higher Himalaya (HH), Lesser Himalaya (LH), and the Siwaliks (SW)
- These sections are confined by major faults including the South Tibetan Detachment (STD), Main Central Thrust (MCT), Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT).
- In the eastern Himalaya, the MFT and The Indian plate is converging in north easterly direction approximately at the rate of 40–50 mm/year

From history to hitherto: *Timeline and tales of earthquakes in Bhutan*

- The continuous convergence of the Indian Plate beneath the Eurasian Plate and has resulted in some of the greatest earthquakes in history, such as the Shillong (1897), Kangra (1905), Bihar–Nepal (1934), and Assam (1950), within 53 years.
- The seismic activities of the eastern to central Himalaya between central Nepal and Arunachal Pradesh remains vaguely understood due to sparse records of the timing and size of major historical earthquakes.
- HISTORICAL EARTHQUAKES IN BHUTAN

➢ 1150

➢ 1713

➢ 1941, 1960

➢ 2003

➢ 2006

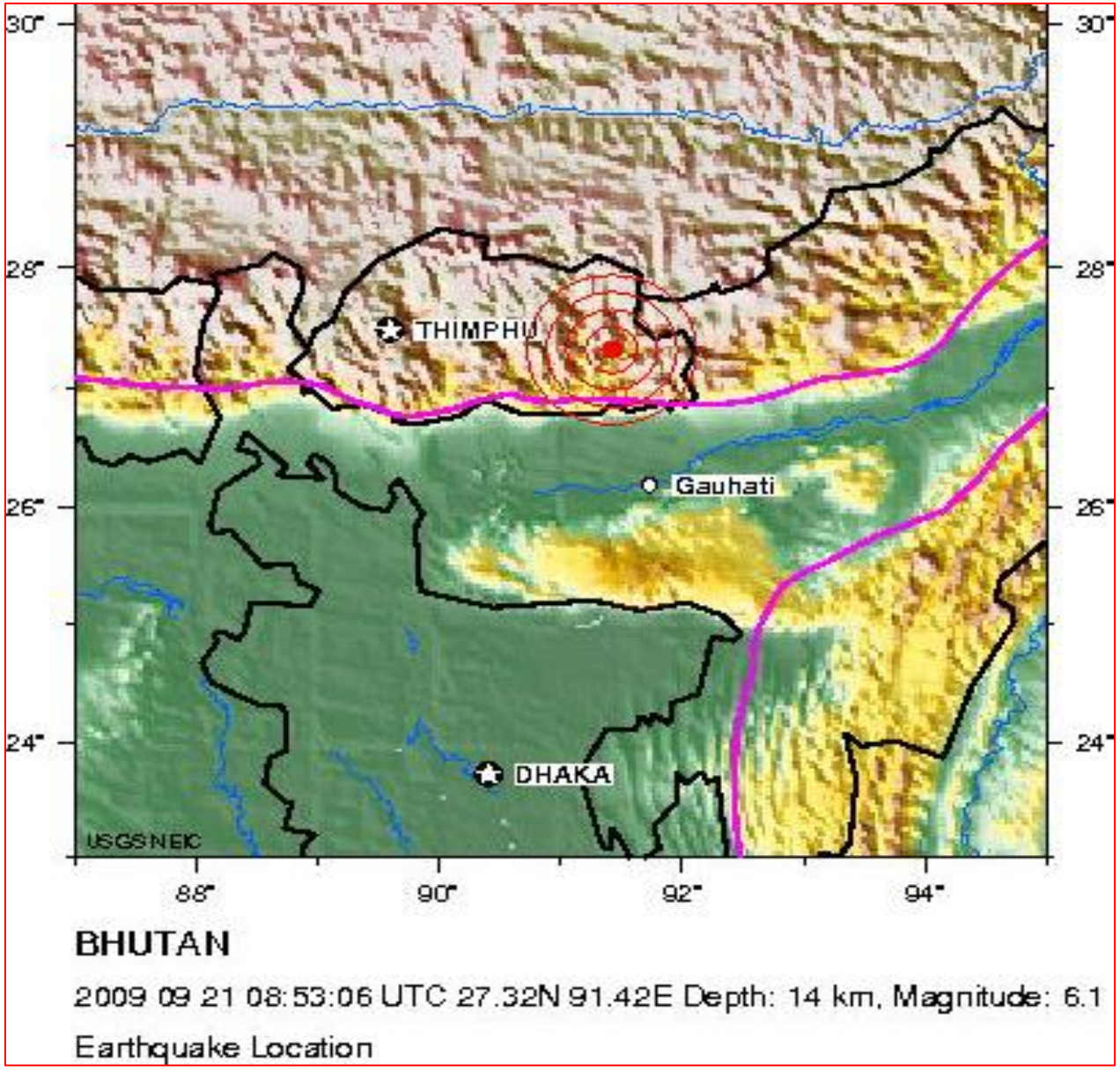
➢ 2009

➢ 2011

➢ 2021

Mongar Earthquake (2009)

- This earthquake occurred at 2:53 pm local time on September 21, 2009.
- The United States Geological Survey estimated its moment magnitude to be 6.1.
- The epicenter :180 km east of the capital Thimphu, in Mongar District and the estimated depth was 14 km.
- The earthquake caused 12 deaths and 47 injuries.
- The earthquake affected 4950 households- 462 collapsed or were severely damaged (beyond repair), 884 sustained major damage, and 1335 sustained partial damage, and 2269 suffered minor damage.



Sikkim-Nepal Border Earthquake (2011)

- The 2011 Sikkim–Nepal border earthquake occurred on September 18, 2011.
- The focal depth -~35 km, moment magnitude to be 6.1 - the United States Geological Survey (USGS).
- The recorded peak ground acceleration at Gangtok and Kathmandu were 0.15 g and 0.05 g, respectively (EERI 2012; Gautam 2017),
- Damaged 7965 buildings in Bhutan
- This earthquake caused one fatality and 14 injuries
- Of the affected residential buildings, 345 collapsed or were damaged beyond repair, 1660 suffered major damage, and 5960 suffered minor damage. The
- PDNA estimated losses of US$15.8 million - residential buildings.

US$24.46 million

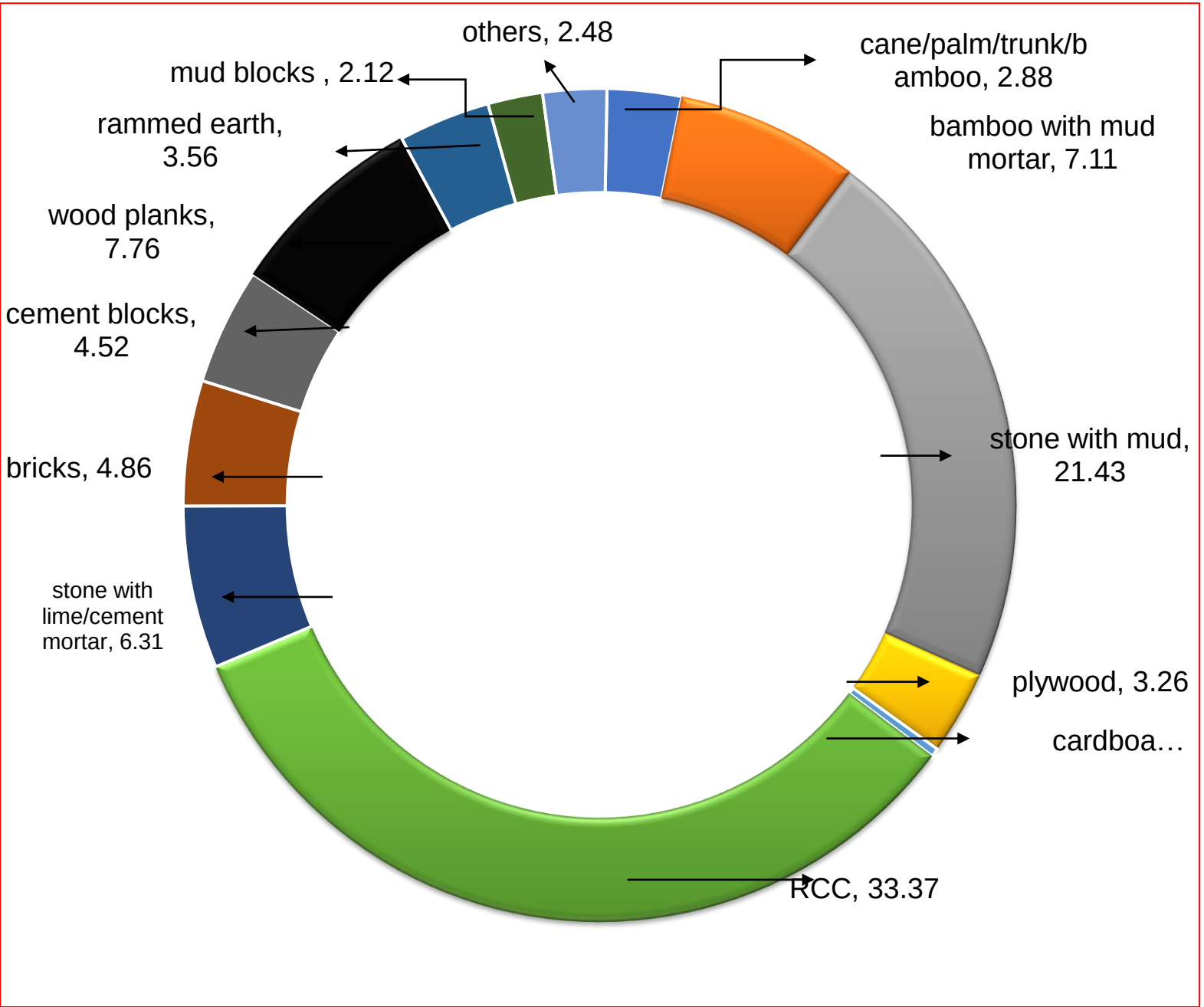
US$0.34 million -government and public buildings

US$6.96 million -cultural heritage structures

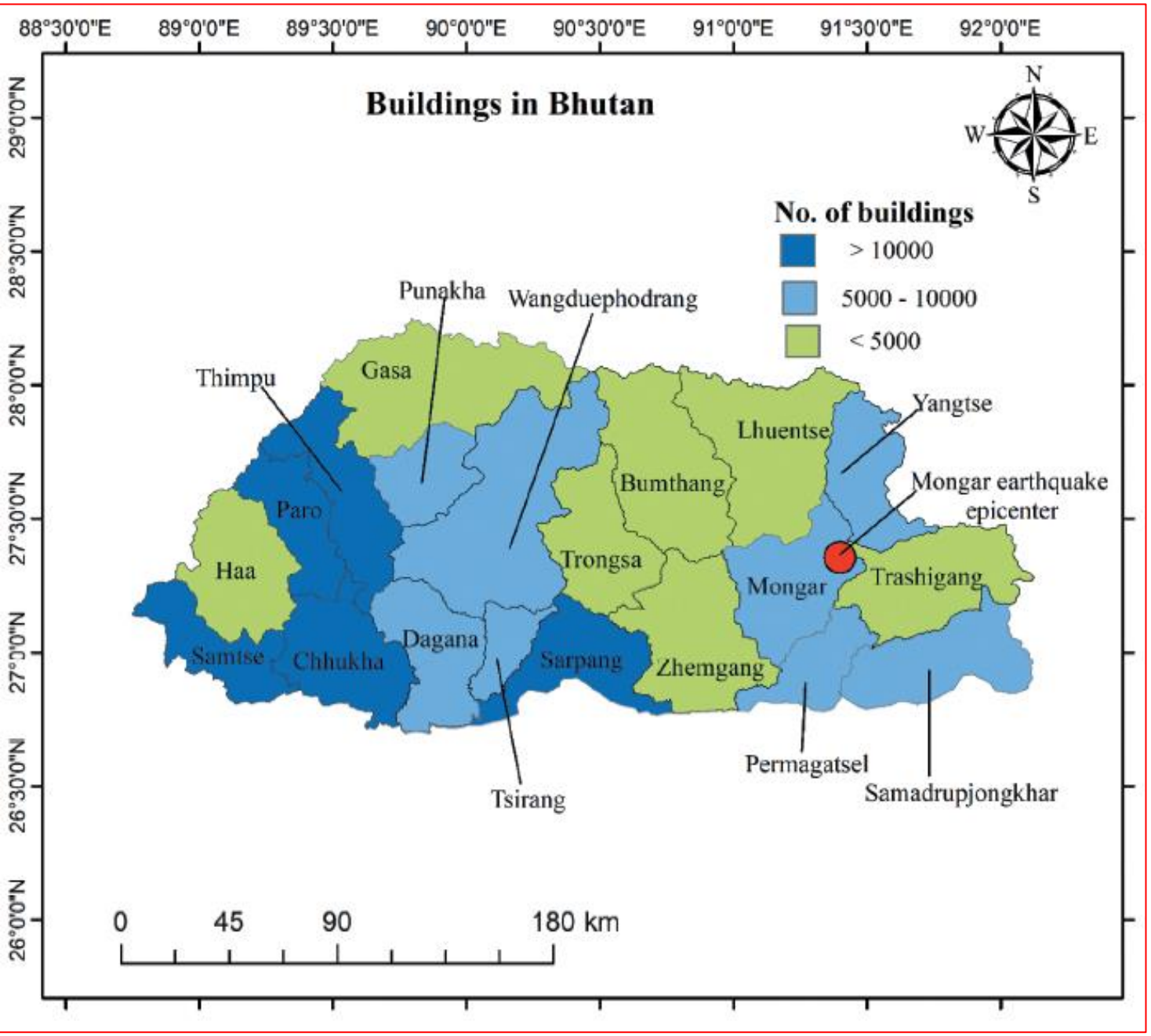
US$0.22 million -school and educational buildings

US$0.12 million -agricultural infrastructure

Taxonomy and Vulnerability of Bhutanese Buildings



- **Fig:** The 2017 census data classifies Bhutanese buildings into 13 categories based on construction.
- Reinforced concrete (RCC) buildings constitute 33.4%
- Masonry construction comprises 42.81%.
- Stone masonry in mud mortar constructions 21.4%
- The rest are classified as "other building." This category comprises wooden (7.76%), wattle and daub (7.11%), plywood (3.26%), cane/palm/trunk/bamboo (2.88%), other (2.48%), and cardboard (0.33%).



- Number of buildings in each district per the 2017 database is mapped in Fig:. The south-western districts of Bhutan are more populated than the eastern and northern districts.
- Three categories are defined as per the number of buildings: districts having more than 10,000 buildings; districts having 5000–10,000 buildings, and districts having less than 5000 buildings.

Seismic Vulnerability of Vernacular Residential Buildings in Bhutan

Research Article

Seismic Vulnerability of Vernacular Residential Buildings in Bhutan

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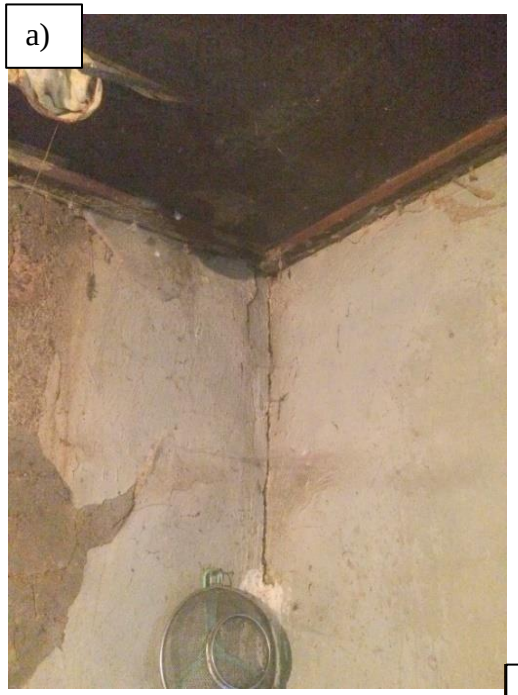
- The study on seismic hazards in Bhutan was performed and the vulnerability of Bhutanese vernacular constructions derived from damage caused by two earthquakes that occurred in 2009 and 2011.
- EMS-98 scale : Each building typology is assigned most likely, probable, and rare vulnerability class.
- Due to differences in workmanship and quality of construction materials, the European vulnerability classification may not be directly applicable to the Bhutanese building stock.
- However, preliminary understanding of vulnerability and prioritization in seismic strengthening could be achieved.

Taxonomy and vulnerability of Bhutanese buildings.

Building type	Indication	Description	Vulnerability classes					
			A	B	C	D	E	F
Others	O1	Cane/palm/trunk/bamboo						
	O2	Wattle and daub						
	O3	Plywood						
	O4	Carboard						
	O5	Wood planks						
Masonry	M1	Stone in mud						
	M2	Bricks						
	M3	Stone in lime/cement						
	M4	Cement blocks						
	M5	Rammed earth						
	M6	Mud blocks						
Reinforced concrete	RC1	without earthquake resistant design						
	RC2	with earthquake resistant design						
Vulnerability:		Most likely		Probable			Rare	

Key damages and Interpretations

a)



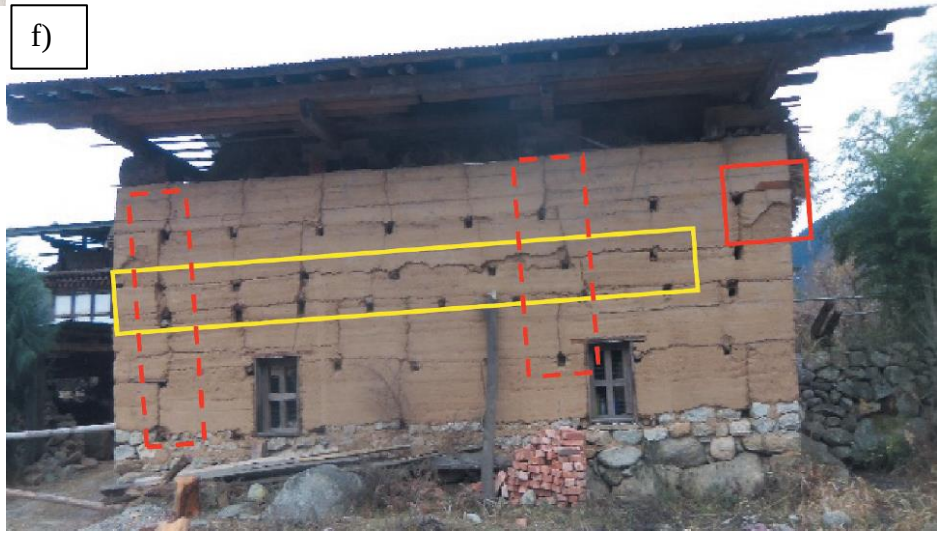
b)

c)

d)

e)

f)



Source: DGM, DDM, MoWHS, DDMOs

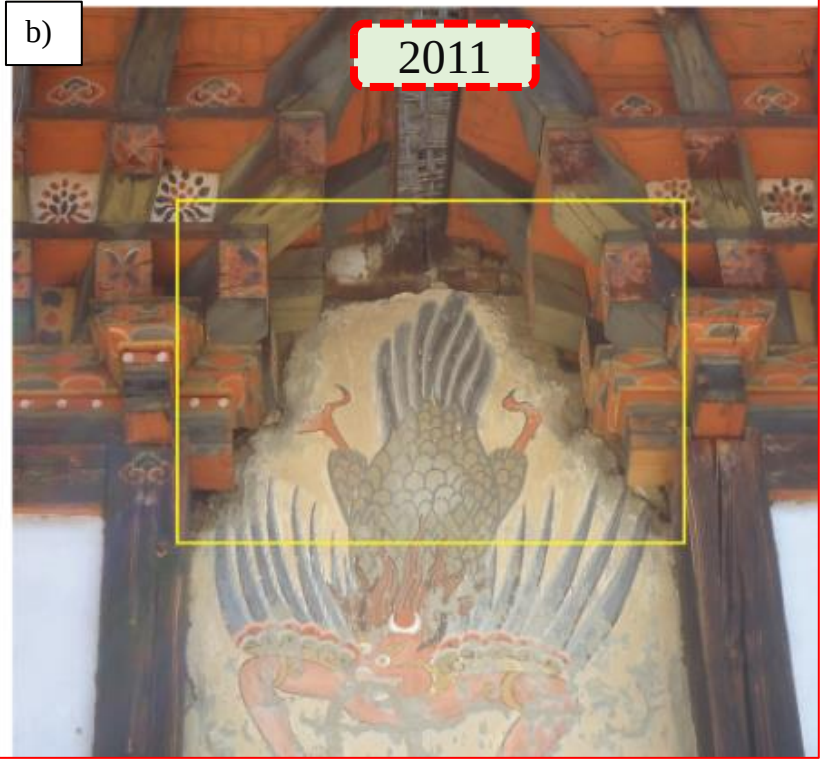
Rabsel Effect! ECCENTRICITY?

a)

2009

b)

2011

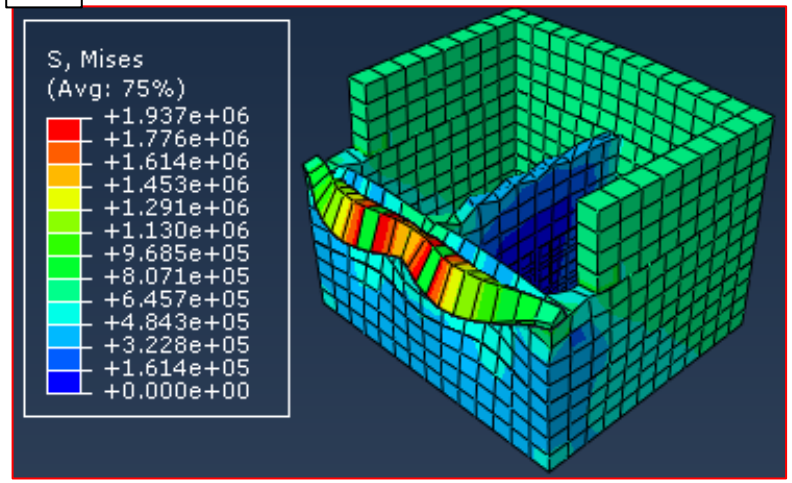


2021

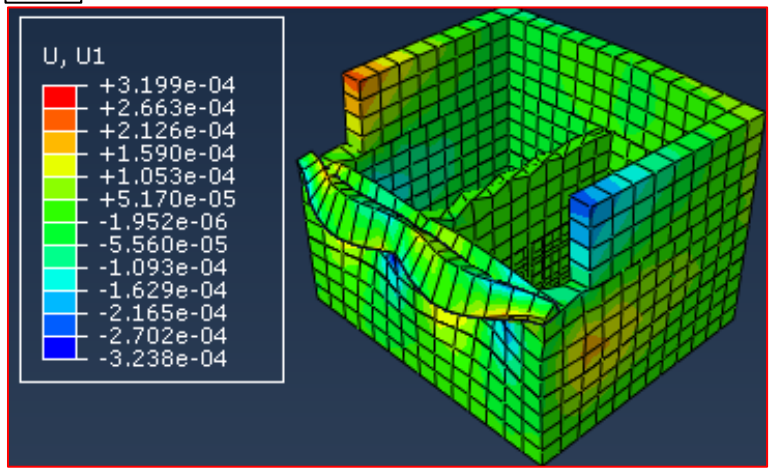
c)

Source: DGM, DDM, MoWHS, DDMOs

e)



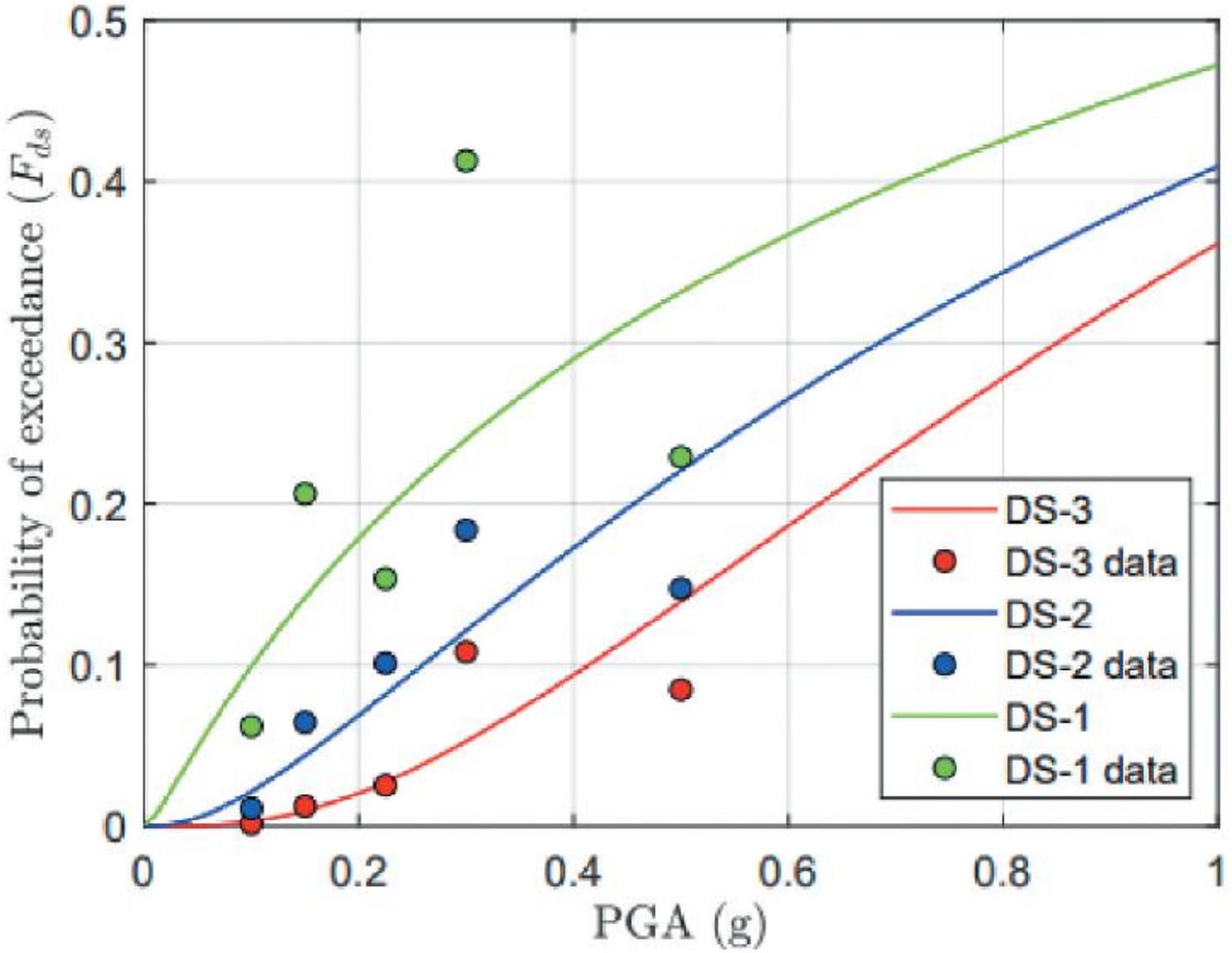
f)

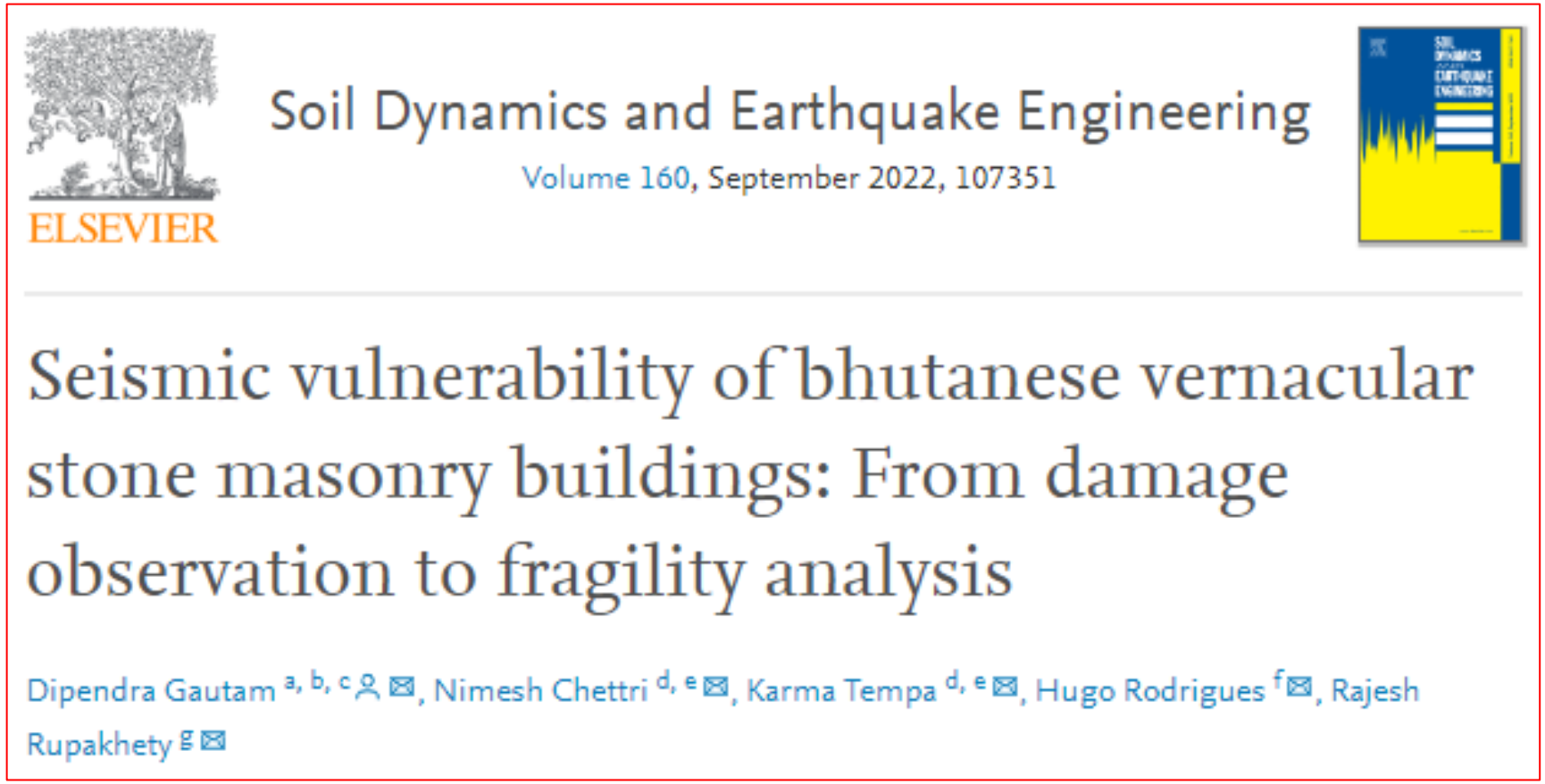


3rd EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING & SEISMOLOGY
BUCHAREST, ROMANIA, 2022

Debunking seismic vulnerability of Bhutanese buildings

Fragility Functions for Bhutanese Vernacular Stone Masonry Buildings





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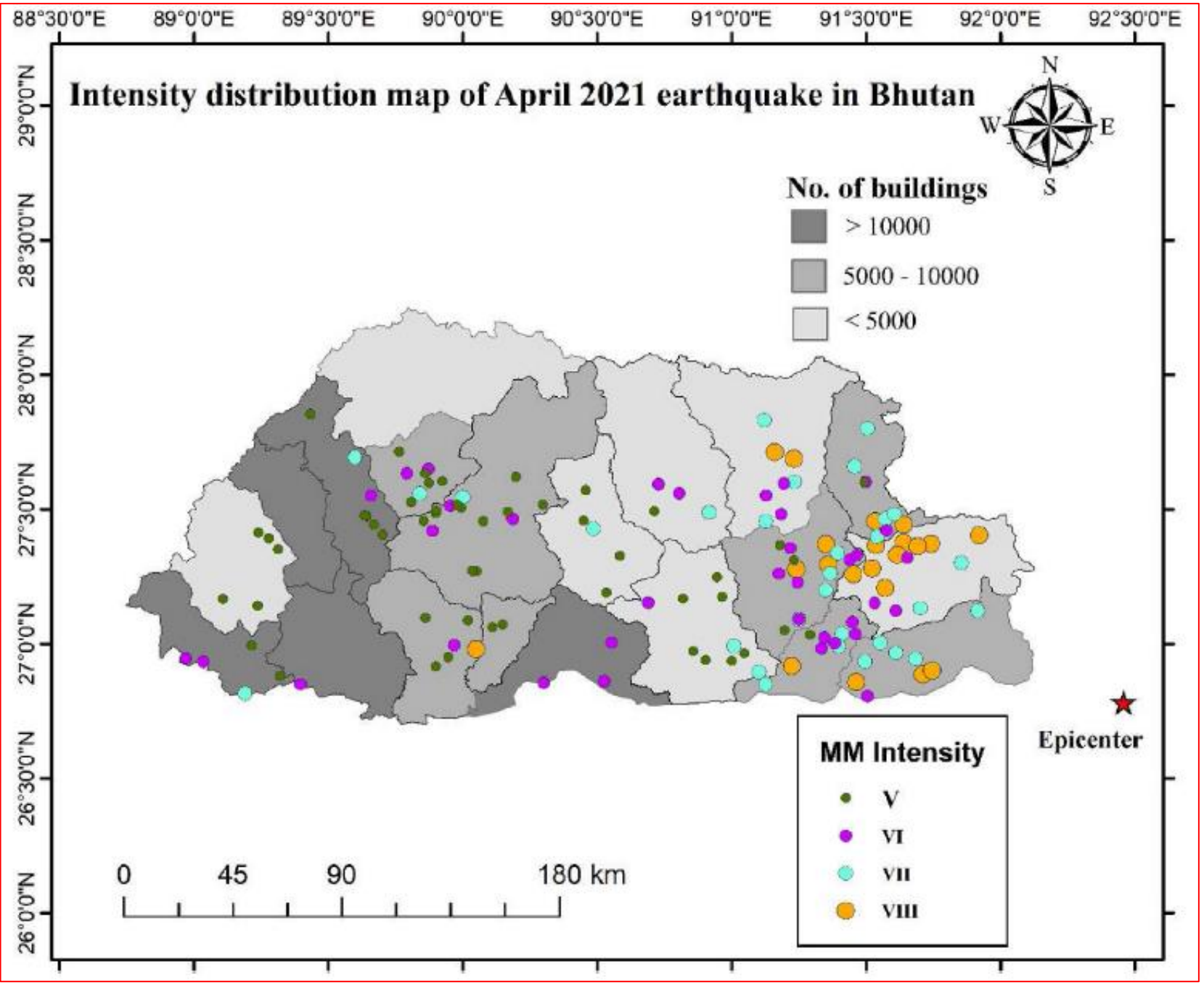
Seismic vulnerability of bhutanese vernacular stone masonry buildings: From damage observation to fragility analysis

Dipendra Gautam [a, b, c], Nimesh Chettri [d, e], Karma Tempa [d, e], Hugo Rodrigues [f], Rajesh Rupakhety [g]

- On April 28, 2021, an earthquake of moment magnitude (MW) 6 (local magnitude 6.4) occurred in the Indian state of Assam at a depth of 34±1.7 km.
- Six aftershocks of local magnitude ranging between 3.2 and 4.7 occurred within 2.5 h after the mainshock.

- Although the earthquake occurred in far field, Bhutan suffered considerable damage to structures and infrastructures, especially in the eastern districts.

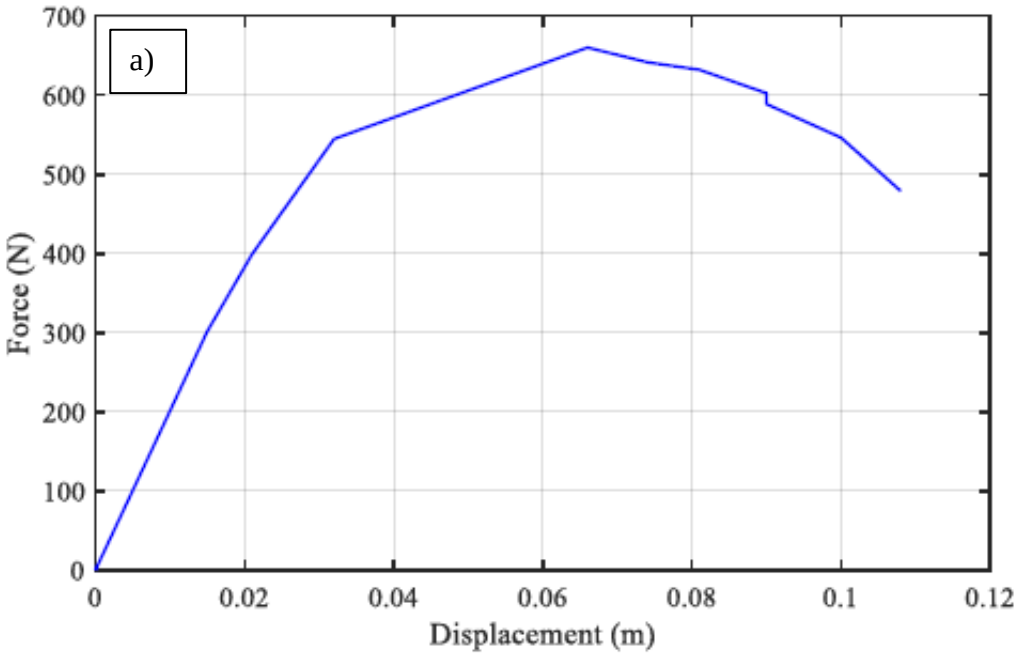


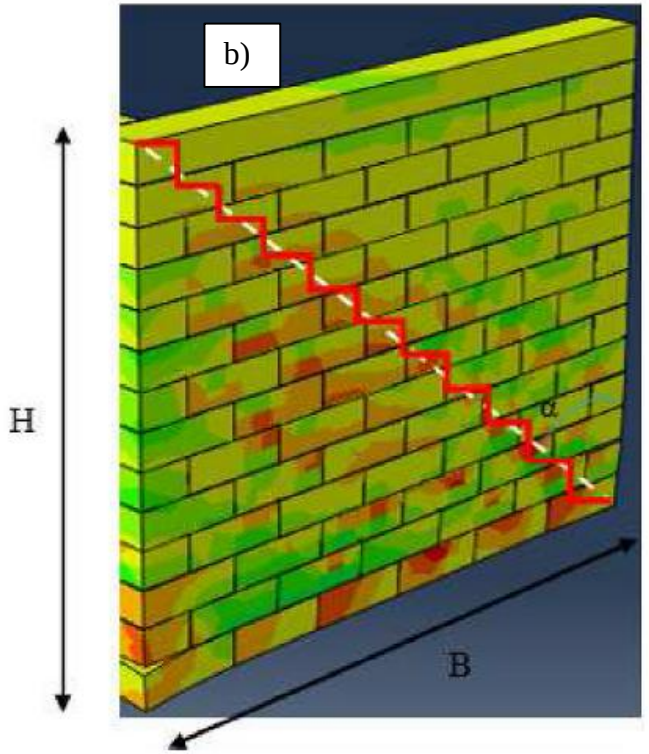
- Fig: MM intensity distribution of the 2021 Sonitpur earthquake in Bhutan
- The estimated PGA in the easternmost district is around 2–10% of acceleration due to gravity.
- The DDMOs collected damage information from 143 villages. Based on the damage descriptions and pictorial evidence, we assigned Modified Mercalli Intensity (MMI) to each village.
- The north-western and western districts were less affected as expected.
- *On the contrary, the intensities based on field observations are much higher than those inferred from the USGS ShakeMap.*

- Table : summarizes the district level damage statistics of the 2021 Sonitpur earthquake. 60% of all buildings (117687) in Bhutan were exposed to the earthquake, among them 16 collapsed, 541 sustained major damage and 2277 sustained minor damage.

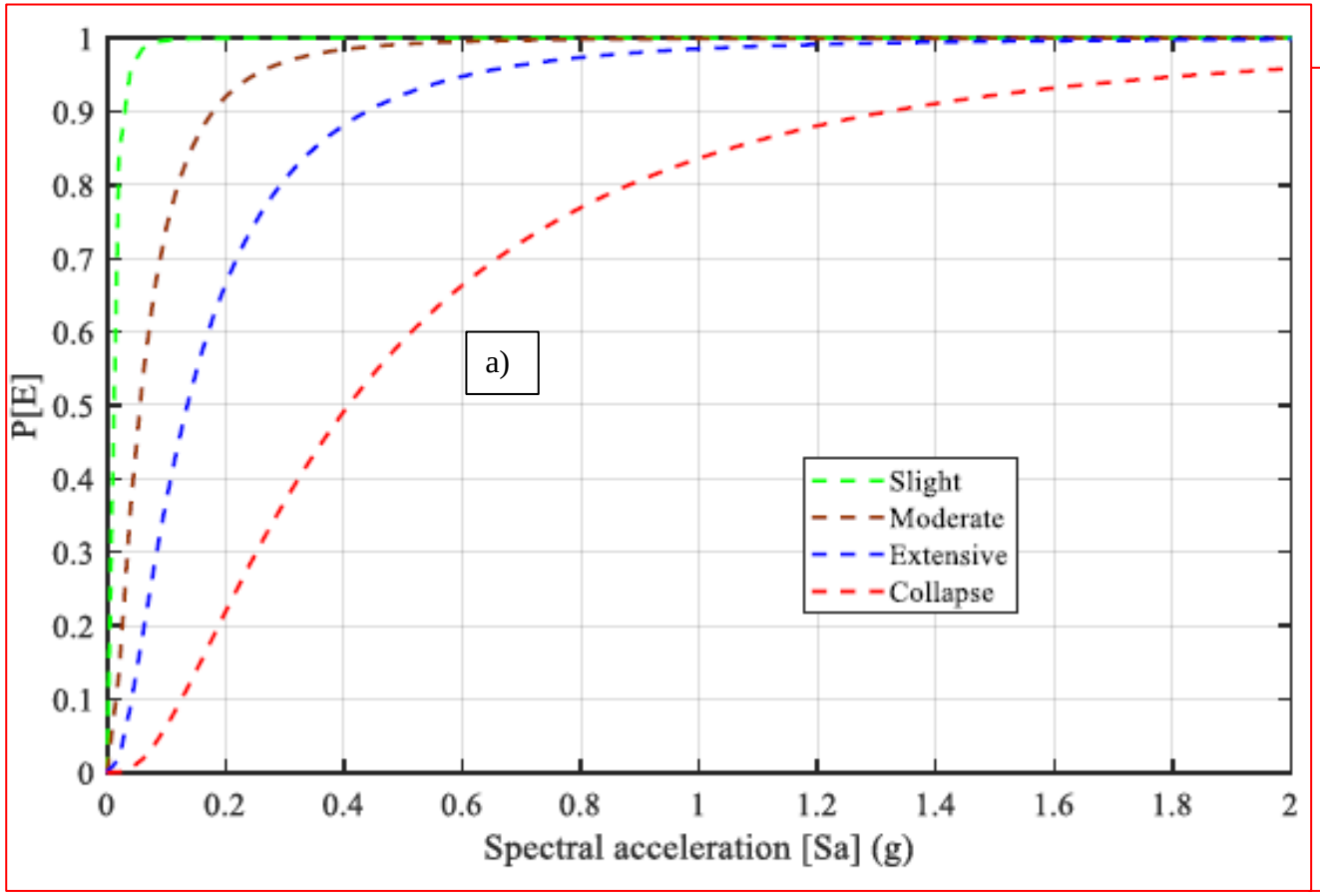
Summary of building damage in Bhutan due to the 2021 Sonitpur earthquake.

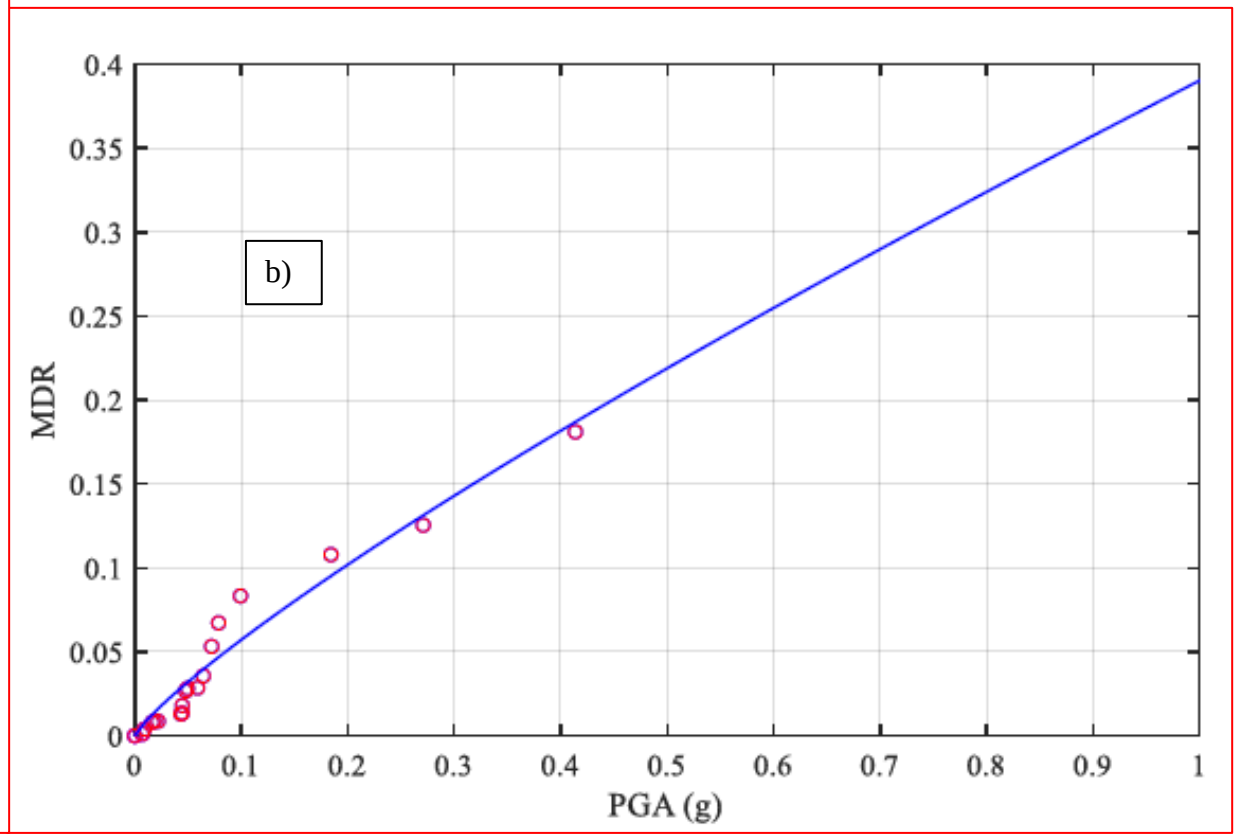
District	# Collapse (beyond repair)	# Major damage (retrofit)	# Minor damages (repair/strengthen)	# Total affected buildings	# Total buildings
Haa	0	0	13	13	2952
Wangdue Phodrang	2	34	124	160	8556
Phuentsholing Thromde	0	0	3	3	6817
Trongsa	0	7	47	54	3690
Bumthang	0	1	44	45	3770
Sarpang	0	0	16	16	10369
Samdrupjongkhar	4	2	131	137	8053
Trashiyangtse	2	54	228	284	3982
Lhuentse	3	32	125	160	3111
Mongar	2	76	316	394	8640
Dagana	0	14	39	53	5671
Trashigang	2	254	840	1096	10720
Pemagatshel	1	67	189	257	6075
Tsirang	0	0	3	3	5063
Zhemgang	0	0	41	41	3803
Samtse	0	0	15	15	14537
Thimphu	0	0	41	41	5799
Punakha	0	0	62	62	6079
Total	16	541	2277	2834	117687





- Fig. a) shows the pushover curve for the stone masonry building.
- The pushover curve was used to define the four damage states: slight, moderate, extensive, and collapse.
- We also performed nonlinear time history analysis (*Gorkha, Kobe, Koceali and Imperial Valley earthquake records*) to obtain demand values for the case study building.
- Fig. b) Diagonal crack showing the **rocking sliding** behavior of stone masonry wall.
- Analytical vulnerability model + Mechanical vulnerability functions





- Fig a). shows that Bhutanese vernacular stone masonry buildings are expected to observe extensive damage at a spectral acceleration as low as 0.2g.
- Thus, it can be concluded that the Bhutanese stone masonry constructions are highly vulnerable to moderate to strong earthquakes.

Earthquake Damage to Vernacular Buildings in Bhutan :*Lessons Learned*

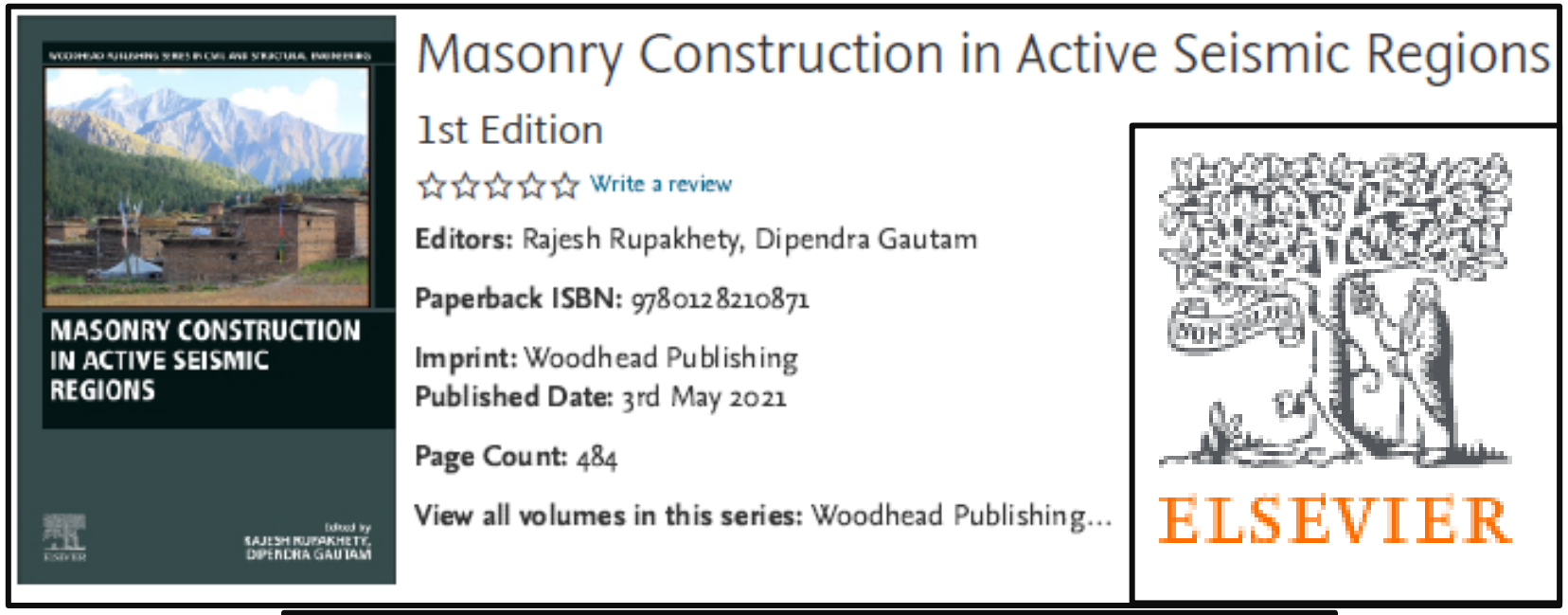
- The losses of the past earthquake have sensitized Bhutanese Engineers to come up with measures to assess hazard and post damages caused by earthquake.

- There is also an immediate need of seismic hazard studies and formulation of new building codes compliant to seismic hazard and construction trends and techniques in Bhutan.

- Load path irregularity, structural integrity, lack of aseismic components are among the most significant factors that trigger or aggravate damage to Bhutanese masonry buildings.

- The vulnerability function highlights that even at low shaking intensity, Bhutanese stone masonry buildings are expected to sustain significant damage. Similarly, analytical modeling confirmed that rocking-sliding mechanism is prominent, whereas toppling is usually not occurred in stone masonry buildings. Both analytical and empirical vulnerability analyses can be improved with experimentally identified modeling parameters and robust database.

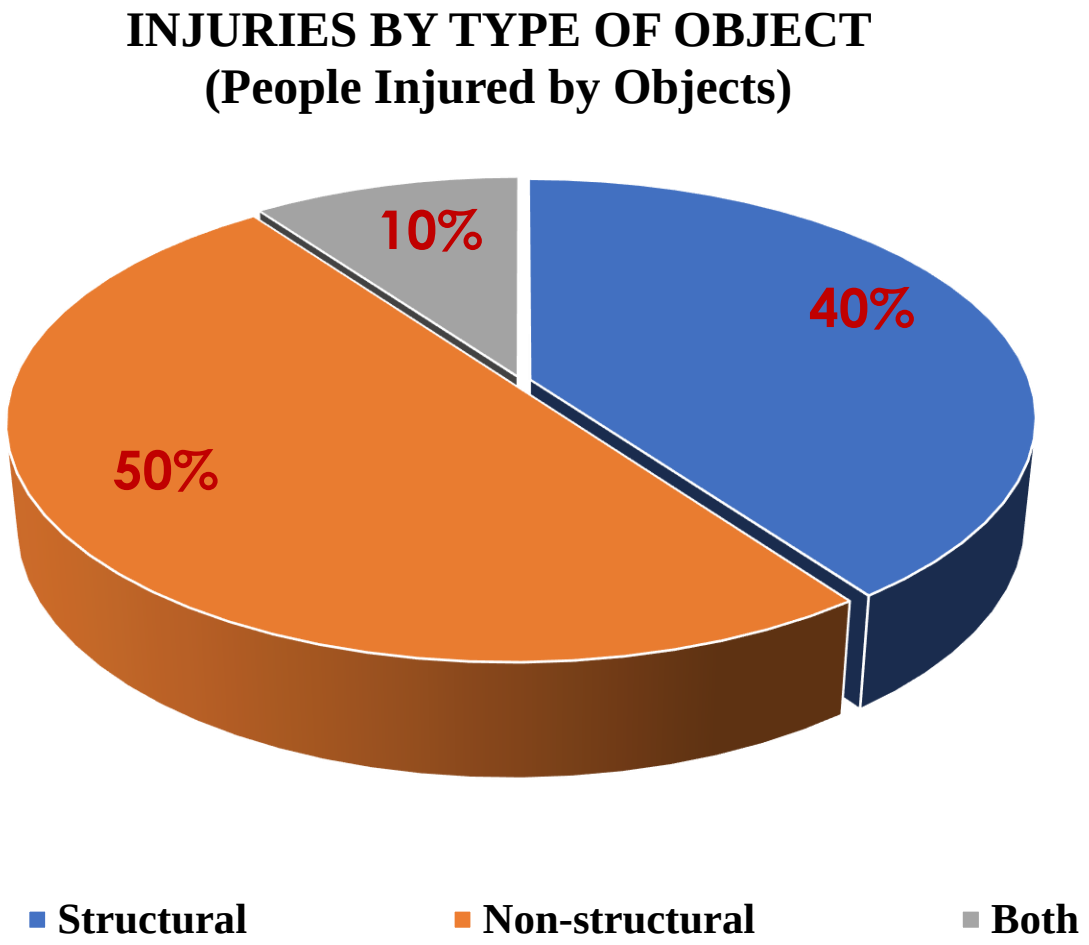
- Strengthening and beyond: *Comparison of various retrofitting approaches for Bhutanese residential buildings*



Insights : ongoing research in CST

1. NON-STRUCTURAL HAZARD (FALLING HAZARDS) MITIGATION

FALLING HAZARDS



M. Petal, 2004: Research findings from 1999; Kocaeli earthquake

a)

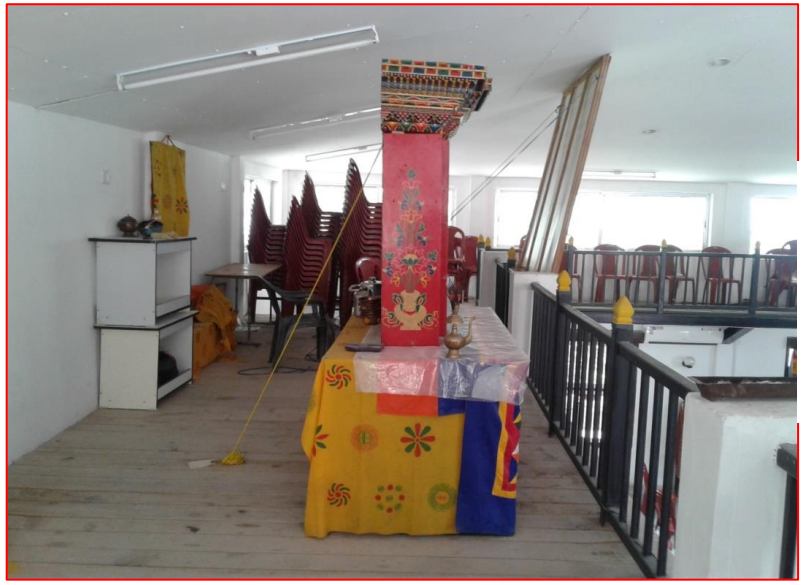
Source: DGM, DDM, MoWHS, DDMOs

b)

Altar

a)

b)



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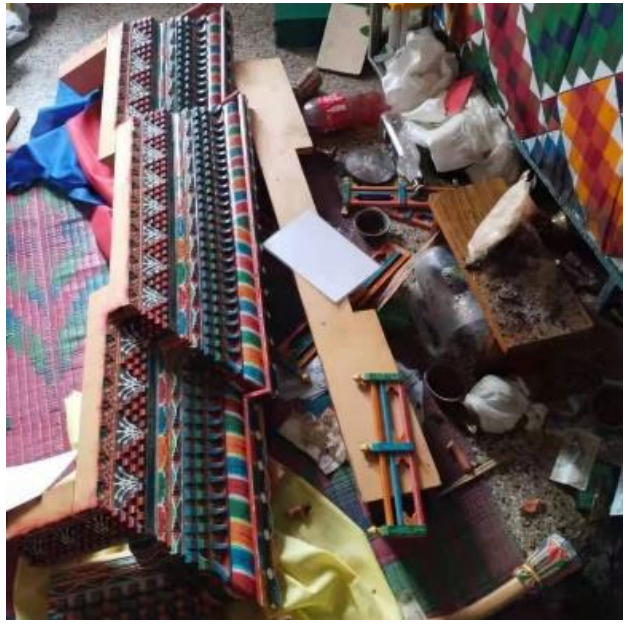


2021

d)

Source: DGM, DDM, MoWHS, DDMOs

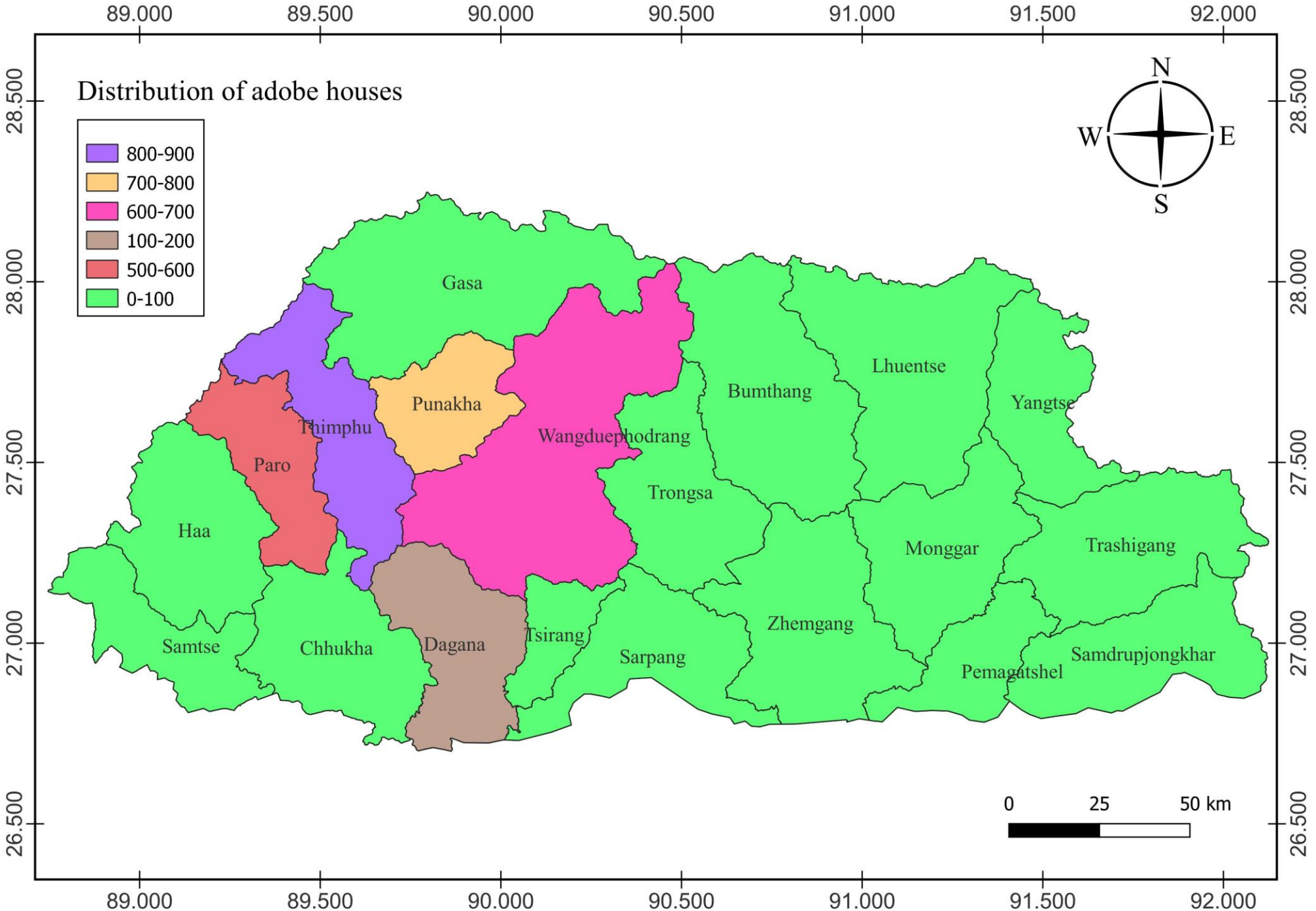
Insights : ongoing research in CST

2. Seismic Performance of Bhutanese Abode (Mud bricks) house

a)

b)

c)


Distribution of adobe houses
800-900
700-800
600-700
100-200
500-600
0-100
N
W
E
S
89.000
89.500
90.000
90.500
91.000
91.500
92.000
28.500
28.000
27.500
27.000
26.500
Gasa
Punakha
Thimphu
Paro
Haa
Wangduephodrang
Bumthang
Lhuentse
Yangtse
Trongsa
Monggar
Trashigang
Samtse
Chhukha
Dagana
Tsirang
Sarpang
Zhemgang
Pemagatshel
Samdrupjongkhar
0
25
50 km

a)

b)

ACKNOWLEDGEMENT

- *Some of the information and images available here are extracted from report of DDM, DGM and MoWHS. This materials is solely for educational purposes. The author would like to acknowledge the source materials.*

བཀའ་དྲིན་ཆེ་ལགས།

Thank You!