Collection of Loss Data and Development of Vulnerability Models

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Abbreviations

Adobe		Sun-dried (or air-dried), unfired mud (clay) masonry, where the clay is cast into blocks (and sometimes into bricks) and then laid (https://taxonomy.openquake.org/terms/adobe-blocks-ado)
BGS	British Geological Survey	An organisation providing expert advice in all areas of geoscience to the UK government and internationally
CoV	Coefficient of Variation	
DesInventar	Global Disaster Loss Collection Initiative	
DMD	Disaster Management Department	Prime Minister's Office of Tanzania focused on disaster risk
DPNet	Disaster Preparedness Network	
DRM	Disaster Risk Management	
EMDAT	Emergency Events Database	
EO	Earth Observation	
Fathom		Provides innovative flood modelling and analytics, based on extensive flood risk research
Fragility		Fragility models describe the likelihood of exceeding a number of damage states conditioned on a ground motion intensity measure (e.g. PGA)
g		Unit of acceleration ($9.81 m/s^2$)
GEM	Global Earthquake Model	Non-profit organisation with the remit to calculate and communicate earthquake risk worldwide.
GoN	Government of Nepal	
HH	Household	
HOT	Humanitarian OpenStreetMap Team	A global non-profit organisation that uses collaborative technology to create editable maps for the world.
IM	Intensity Measure	
ImageCat		International risk management innovation company supporting the global risk and catastrophe management needs of the insurance industry, governments and NGOs
IPP	International Partnership Programme	
KPa	Kilo Pascal	
KTP		Kirtipur

METEOR	Modelling Exposure Through Earth Observation Routines	
Mw	Moment Magnitude	
NOAA	National Oceanic and Atmospheric Administration	
NSET	National Society for Earthquake Technology	Non-governmental organisation working on reducing earthquake risk in Nepal and abroad
ODA	Official Development Assistance	
OPM	Oxford Policy Management	Organisation focused on sustainable project design and implementation for reducing social and economic disadvantage in low-income countries
PGA	Peak Ground Acceleration	
PTN		Patan
RC	Reinforced Concrete	A structure in reinforced concrete is composed by concrete (composite material consisting of cement, coarse aggregate (crushed stone), fine aggregate (sand) and water), that is reinforced by metal, usually steel rods or bars cast into the concrete (https://taxonomy.openquake.org/terms/concrete-reinforced--cr).
Rebar		Reinforcing steel embedded within a concrete structure
SA	Spectral Acceleration	
Spandrel		Spandrel are load-bearing beams provided at each flood level around the perimeter of a masonry construction that extend from column to column.
THM		Thimi
TVU		TVU
UKSA	United Kingdom Space Agency	
UNDP	United Nation Development Programme	
URM	Unreinforced Masonry	A unreinforced masonry structure is composed by individual units (such as stones or bricks), which are often laid in and bound together by mortar (https://taxonomy.openquake.org/terms/masonry-unreinforced--mur)
VEI	Volcanic Explosivity Index	A numeric scale to measure the relative explosivity of historical volcanic eruptions.
Vulnerability		Vulnerability models describe the probability of loss (economic loss, fatalities, downtime) conditioned on an ground motion intensity measure (e.g. PGA).

Wythe		A wythe is one of the two concrete layers aggregated into a precast concrete sandwich wall.
WP	Work Package	
μ		Logarithmic mean
σ		Logarithmic standard deviation

1. METEOR Project Introduction

1.1. Project Summary

Project Title	Modelling Exposure Through Earth Observation Routines (METEOR): EO-based Exposure, Nepal and Tanzania
Starting Date	08/02/2018
Duration	36 months
Partners	UK Partners: The British Geological Survey (BGS) (Lead), Oxford Policy Management Limited (OPM), SSBN Limited International Partners: The Disaster Management Department, Office of the Prime Minister – Tanzania (DMD), The Global Earthquake Model (GEM) Foundation, The Humanitarian OpenStreetMap Team (HOT), ImageCat, National Society for Earthquake Technology (NSET) – Nepal
Target Countries	Nepal and Tanzania for "level 2" results and all 47 Least Developed ODA countries for "level 1" data
IPP Project	IPPC2_07_BGS_METEOR

Table 1.1: METEOR Project Summary

1.2. Project Overview

At present, there is a poor understanding of population exposure in some Official Development Assistance (ODA) countries, which causes major challenges when making Disaster Risk Management decisions. Modelling Exposure Through Earth Observation Routines (METEOR) takes a step-change in the application of Earth Observation exposure data by developing and delivering more accurate levels of population exposure to natural hazards. METEOR is delivering calibrated exposure data for Nepal and Tanzania, plus 'Level-1' exposure for the remaining Least developed Countries (LDCs) ODA countries. Moreover, we are: (i) developing and delivering national hazard footprints for Nepal and Tanzania; (ii) producing new vulnerability data for the impacts of hazards on exposure; and (iii) characterising how multi-hazards interact and impact upon exposure. The provision of METEOR's consistent data to governments, town planners and insurance providers will promote welfare and economic development and better enable them to respond to the hazards when they do occur.

METEOR is co-funded through the second iteration of the UK Space Agency's (UKSA) International Partnership Programme (IPP), which uses space expertise to develop and deliver innovative solutions to real world problems across the globe. The funding helps to build sustainable development while building effective partnerships that can lead to growth opportunities for British companies.

1.3. Project Objectives

METEOR aims to formulate an innovative methodology of creating exposure data through the use of EO-based imagery to identify development patterns throughout a country. Stratified sampling technique harnessing traditional land use interpretation methods modified to characterise building patterns can be combined with EO and in-field building characteristics to capture the distribution of building types. These protocols and standards will be developed for broad application to ODA countries and will be tested and validated for both Nepal and Tanzania to assure they are fit-for-purpose.

Detailed building data collected on the ground for the cities of Kathmandu (Nepal) and Dar es Salaam (Tanzania) will be used to compare and validate the EO generated exposure datasets. Objectives of the project look to: deliver exposure data for 47 of the least developed ODA countries, including Nepal and Tanzania; create hazard footprints for the specific countries; create open protocol; to develop critical exposure information from EO data; and capacity-building of local decision makers to apply data and assess hazard exposure. The eight work packages (WP) that make up the METEOR project are outlined below in section 1.4.

1.4. Work Packages

Outlined below are the eight work packages that make up the METEOR project, which are led by various partners. Table 1.2 provides an overview of the work packages together with a brief description of what each of the work packages cover.

Table 1.2: Overview of METEOR Work Packages

Work Package	Title	Lead	Overview
WP.1	Project Management	BGS	Project management, meetings with UKSA, quarterly reporting and the provision of feedback on project deliverables and direction across primary stakeholders.
WP.2	Monitoring and Evaluation	OPM	Monitoring and evaluation of the project and its impact, using a theory of change approach to assess whether the associated activities are leading to the desired outcome.
WP.3	EO Data for Exposure Development	ImageCat	EO-based data for exposure development, methods and protocols of segmenting/classifying building patterns for stratified sampling of building characteristics.
WP.4	Inputs and Validation	HOT	Collect exposure data in Kathmandu and Dar es Salaam to help validate and calibrate the data derived from the classification of building patterns from EO-based imagery.
WP.5	Vulnerability and Uncertainty	GEM	Investigate how assumptions, limitations, scale and accuracy of exposure data, as well as decisions in data development process lead to modelled uncertainty.

WP.6	Multiple Hazard Impact	BGS	Multiple hazard impacts on exposure and how they may be addressed in disaster risk management by a range of stakeholders.
WP.7	Knowledge Sharing	GEM	Disseminate to the wider space and development sectors through dedicated web-portals and use of the Challenge Fund open databases.
WP.8	Sustainability and Capacity-Building	ImageCat	Sustainability and capacity-building, with the launch of the databases for Nepal and Tanzania while working with in-country experts.

2. Collection of Loss and Damage Data: Introduction

Understanding the extent of adverse effects of future disasters is imperative in planning and implementing risk mitigation and preparedness policies. The most common approach to estimate disaster impact is through probabilistic risk assessment. Risk assessment methodologies involve complex models, characterised by a large number of variables. These variables warrant the exploration of the sensitivity of the output to variations in the input parameters. For most natural perils, the hazard model considers a wide spectrum of uncertainties. However, the uncertainties associated with damage and loss calculations can be equally large, as it is compounded by the uncertainties in the exposure classification and vulnerability of each building class. Losses expressed in economic terms are subjected to additional uncertainties due to the assignment of cost to physical damage. Unlike most of the epistemic uncertainties in the hazard component that can be resolved by more data from future events, the epistemic uncertainty in the characterisation of the vulnerability can only be reduced by understanding the mechanism and process of damage and losses from historical events.

The current deliverable focuses on the collection of direct damage and loss data for vulnerability characterisation, and development or compilation of fragility and vulnerability curves suitable for scenarios and probabilistic risk assessment. This dataset will further improve the knowledge and understanding of the built environment in Nepal and Tanzania. Moreover, the number of affected people, damaged buildings and total economic losses from past events are critical to assess the reliability and accuracy of existing fragility and vulnerability models.

For each country, three natural perils are considered; namely earthquake, flood and landslide for Nepal and earthquake, flood and volcano for Tanzania. For the purpose of this work, only data regarding physical destruction caused by disasters to humans and properties (i.e. damage) and economic and human losses were considered. Indirect impacts such as business interruption or increase in the unemployment were excluded from the scope of this work, and as such will not be reported.

2. Past Disasters in Nepal

Nepal is highly susceptible to a range of geophysical and hydro-meteorological hazards, including earthquakes, floods and landslides (PFRNA 2017). Steep and rugged mountain topography together with a geology (that is prone to landslides and ground shaking amplification), active tectonics, and extreme weather has made the country prone to multiple natural hazards (Acharya, *et al.,* 2006). These hazards have caused significant damage in the past, weakening the country's ecosystem, economy and sustainable development. The World Bank describes Nepal as a disaster hotspot exposed to multiple hazards (Dilley, *et al.,* 2005). For example, the 2015 Gorkha earthquake was estimated to have losses equivalent to a third of Nepal Gross Domestic Product (GoN, 2019). The total damage caused by the 2017 floods was about 584.7 million USD, which amounts to almost 3% of Nepal's Gross Domestic Product (PFRNA, 2017).

Figure 2.1 to Figure 2.3 show loss and damage data in terms of fatalities, affected population and economic loss. Earthquakes, floods and landslides account for more than 90% of the economic impact due to natural hazards in Nepal (EMDAT, 2019).

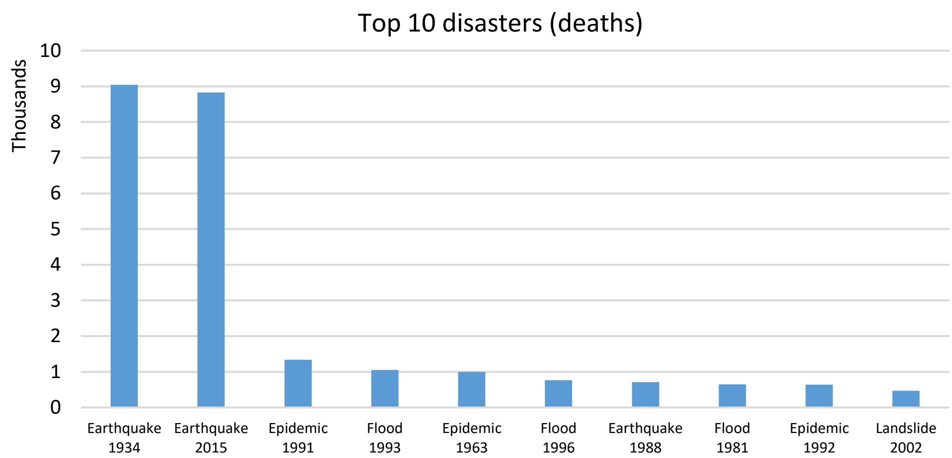


Figure 2.1: Nepal's top 10 disasters between 1901 and 2019 in terms of the number of fatalities (source: EMDAT).

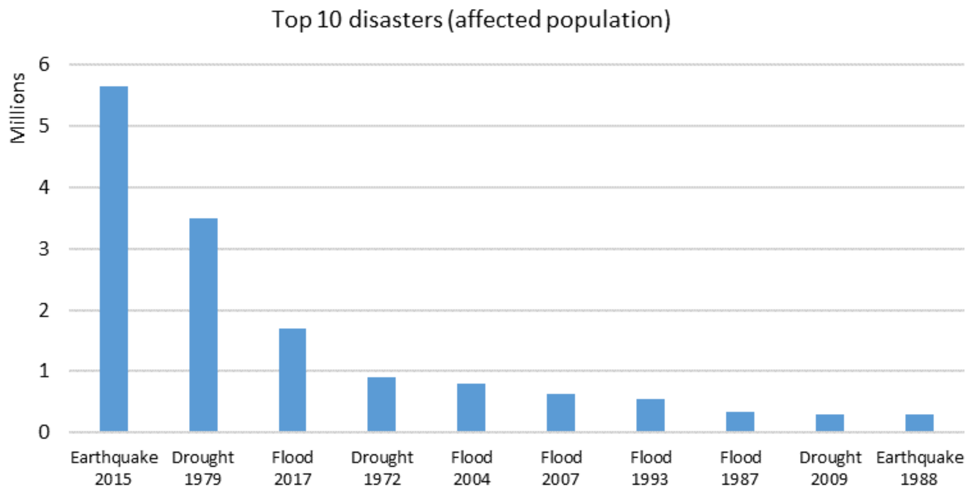


Figure 2.2: Nepal's top 10 disasters between 1901 and 2019 in terms of the number of affected people (source: EMDAT)

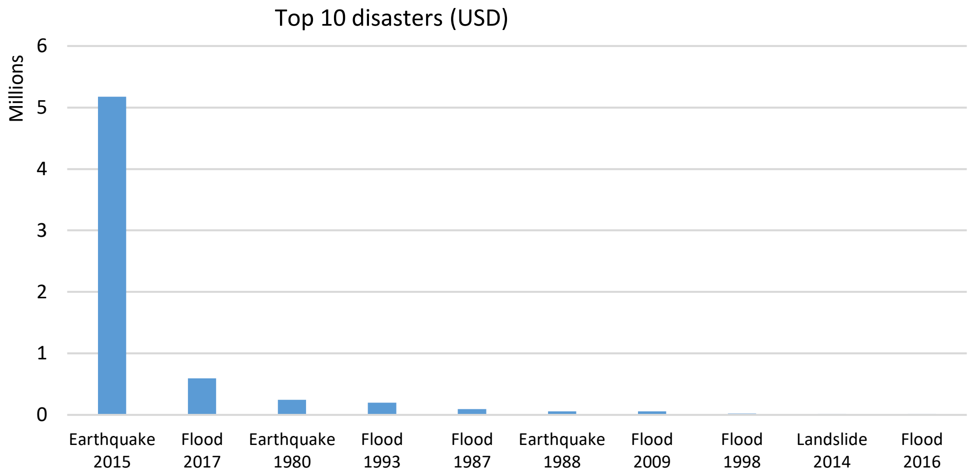


Figure 2.3: Nepal's top 10 disasters between 1901 and 2019 in terms of economic losses (source: EMDAT).

2.1. Earthquakes

The first documented earthquake event in the Nepal dates to 7th June 1255, which destroyed a third of Kathmandu and killed its ruler, King Abhaya Malla (Poudel, 2014). Another earthquake occurred in 1260 during the reign of King Jayadev, and it was also as destructive as the 1255 earthquake. A large number of fatalities were reported followed by an epidemic and intense famine. Many buildings and temples collapsed during this earthquake. Historical records give a limited account of the 1408 earthquake that destroyed Rato Matchendraneth temple. Another event, the 1681 earthquake occurred during the reign of King Sri Niwas Malla and resulted in thousands of deaths and heavy losses. In the months of June and July of 1767, other earthquakes of significant intensity were recorded. Between 1255 and 2015, 17 very strong (> Mw 6) events occurred in Nepal and resulted in the death of almost 50,000 people. Table 2.1 lists the major earthquake events in Nepal from 1255 to 2018.

Table 2.1: List of earthquakes in Nepal from 1255 to 2018 (Bilham, 2004; Dizhur, et al., 2016; GoN, 2019)

Date	Place	Mag.	Deaths	Injuries	Affected	Houses destroyed	Houses damaged	Loss (000$)
07/06/1255	Kathmandu	7.8 Mw	2,200					
1260	Sagarmatha	7.1 Mw	100					
1344	Mechi	7.9 Mw	100					
08/1408	Bagmati zone	8.2 Mw	2,500					
06/1505	Near Saldang, Karnali zone	8.7 Mw	6,000					
01/1681	Northern Kosi zone	8.0 Mw	4,500					
07/1767	Northern Bagmati zone	7.9 Mw	4,000					
26/08/1833	Kathmandu/Bihar	8.0 Mw	6,500					
07/07/1869	Kathmandu	6.5 Mw	750					
28/08/1916	Mahakali Zone	7.7 Mw	3,500					
15/01/1934	Bihar	8.0 Mw	8,519	0	0			0
27/06/1966	Province no. 7	6.3 Mw	80	100	20,000	5,200		1,000
29/07/1980	Western region	6.5 Mw	200	5,600	200,000			245,000
20/08/1988	Kathmandu/Bihar	6.6 Mw	1,091	1,016	300,000			60,000
18/09/2011	Nepal	6.9 Mw	111	89	167,860			0
25/04/2015	Gorkha	7.8 Mw	8,922	17,866	5,621,790	299,588	269,107	5,174,000
12/05/2015	Dolakha and Sindhupalchow	7.3 Mw	213	2,800	5,621,790			
27/11/2016	Mount Ama Dablam, Harikharka	5.4 Mw	1	1		2		
21/06/2017	Dhading	3.2 Mw	1	1				
Total			**49,288**	**27,473**	**11,931,440**	**304,790**	**269,107**	**5,480,000**

2.1.2. 1934 Earthquake

The 1934 earthquake occurred on 15th January at about 2.24pm. The shaking had a magnitude of 8.2 on the Richter scale. The epicenter was in eastern Nepal, about 9.5km south of Mount Everest. Areas where the most damage to life and property occurred extended from Prunea in the east to Champaran in the west and from Kathmandu in the north to Munger in the south. More than 7000 people died and roughly 20% of all buildings were destroyed and another 40% got damaged. In Kathmandu around 25% of all houses were destroyed just like several temples in the old town of Bhaktapur. Damage was worst in houses built with kut-cha-pucca and mud while bamboo houses suffered the least damage (Sapkota, *et al.,* 2016). Table 2.2 provides information concerning the damage and loss for all the towns and cities affected by the 1934 earthquake.

Town, District	Fatality count	Collapsed building	Cracked building	Damaged building	Total buildings affected
Kathmandu valley					
Kathmandu	479	725	3,735	4,146	8,606
Kathmandu vicinity	245	2,892	4,062	4,267	11,221
Patan	547	1,000	4,170	3,860	9,030
Patan vicinity	1,697	3,977	9,442	1,598	15,017
Bhaktapur	1,172	2,359	2,263	1,425	6,047
Bhaktapur vicinity	156	1,444	1,986	2,388	5,818
Total	**4,296**	**12,397**	**25,658**	**17,684**	**55,739**
Eastern mountain districts					
East district 1 (Chautara)	356	9,628	19,391	-	29,019
East district 2 (Ramechhap)	95	4,687	10,738		15,425
East district 3 (Okhald-hunga)	857	21,107	15,548	-	36,655
East district 4 (Bhojpur)	1,597	15,048	5	-	15,053
Dhankuta district	316	6,623	15,120	-	21,743
Ilam district	92	2,316	3,112	-	5,428
Udayapur Gadhi district	552	1,052	3,917	-	4,969
Sindhuli Gadhi district	109	3,486	3,154	-	6,640
Total	**3,974**	**63,947**	**70,985**		**134,932**
Western mountain districts					
West district 1 (Nuwakot)	10	582	1,720	-	2,302
West district 2 (Gorkha)	1	186	461	-	647
West district 3 (Pokhara)	1	19	65	-	84
West district 4	1	8	1	-	9
Chisapani Gadhi district	52	-	18	1,266	1,284
Total	**65**	**795**	**2,268**	**1,266**	**4,329**
Eastern Terai					
Birgunj district	44	3,654	854	2,546	7,054
Mahottari and Sarlahi districts	51	–	4,323	268	4,591
Saptari and Siraha districts	40	87	428	-	515
Biratnagar district	49	13	1	64	78
Jhapa district		-	-	-	-
Total	**184**	**3,754**	**5,610**	**2,884**	**12,248**
Total Nepal	**8,519**	**80,893**	**104,521**	**21,834**	**207,248**

Table 2.2: Fatality count and affected buildings at district level during the Bihar 1934 earthquake (source: Sapkota, et al., 2016)

Figure 2.4: Collapsed buildings during the 1934 earthquake in Nepal (source: Nepalese Times).

2.1.3. Gorkha Earthquake

The Gorkha earthquake occurred on 25th April 2015 at 11:56am with a magnitude of 7.8. The epicenter was east of Gorkha district at Barpack and the hypocenter was at the depth of approximately 8.2km, which is considered shallow and therefore more damaging than earthquakes that originate deeper in the ground (Lizundia, *et al.,* 2017). The event caused tremendous damage and loss to both life and property. It triggered an avalanche on Mount Everest killing 21 people and further triggered another avalanche in the Langtang valley where 250 people were reported missing. The shaking caused considerable damage to lifelines resulting in service interruptions. Electric power generation and distribution were heavily affected (Pehlivan, *et al.,* 2017). Water supply systems also experienced extensive damages such as pipeline breaks, silting of wells, and damage to the office of the Kathmandu Valley water department. The earthquake greatly affected the integrity of buildings in several cities. More than 500,000 buildings were destroyed. Unreinforced masonry houses suffered the most although reinforced concrete structures were significantly damaged (see Figure 2.5). Wood frames performed relatively better except in the case of slope failure or masonry veneer failing (Brzev, *et al.,* 2017).

Common failure mechanisms in RC frames included pounding damage, cracking and spalling of the infill masonry, column shear failures, beam-column joint failure, short column failures and foundation failure. Conditions that contributed to damage include soft storeys, out-of-plane setbacks and overhangs, discontinuous columns, plan irregularities, poor quality constructions and workmanship, inadequate foundation on hill slope, and non-ductile concrete detailing. Field surveys shows damage in low-rise RC infilled is well correlated to the wall index (Karmacharya, *et al.,* 2018). Structural damage in high-rise RC infilled frames were less severe compared with low rise RC infilled frames, though there were buildings with substantial non-structural damage that pose threat to life safety (Lizundia, *et al.,* 2017).

Unreinforced masonry buildings represent a large fraction of the building stock in Kathmandu. They are largely non-engineered and usually constructed without supervision (Varum, *et al.,* 2018). Wall delamination, out-of-plane failure, in-plane damage to arches, diagonal shear cracking in piers, spandrels and walls, shear sliding on mortar bed joints or between storeys, and in-plane rocking and toe crushing of piers were some failure mechanisms observed in the load bearing unreinforced masonry buildings (Dizhur, *et al.,* 2016). Conditions contributing to damage include poor masonry layup, without header connections between wythes or corner stones, missing wood or rebar reinforcement, poor connections between exterior and perpendicular interior walls, weak mortar, heavy mud-fill timber diaphragms with poor connections to walls, and plan and vertical irregularities such as soft storeys. Increased damage was correlated with ridge top locations and hillsides slopes (Lizundia, *et al.,* 2017).

Figure 2.5: Sample building types affected by 2015 Gorkha earthquake. (a) RC infill frames, (b) URM bearing wall and (c) wood frame (source: Lizundia, et al., 2017).

Type of constructions	Site	Not damaged	Damage level			TOTAL
			Slightly damaged	**Moderately damaged**	**Heavily damaged**	
Load-bearing masonry cement mortar	KTP	99	15	6	2	122
	TVU	4	1	1	1	7
	PTN	21	4	4	2	31
	THM	12	2	1	0	15
	Total	**136**	**44**	**12**	**5**	**175**
Load-bearing masonry mud mortar	KTP	26	4	1	0	32
	Total	**26**	**4**	**1**	**0**	**32**
RC infill frame structure	KTP	20	0	0	0	20
	TVU	3	9	0	0	12
	PTN	33	19	2	0	54
	THM	13	3	0	0	16
	Total	**69**	**31**	**2**	**0**	**102**
RC steel masonry	THM	1	0	0	0	1
	Total	**1**	**0**	**0**	**0**	**1**

Table 2.3: Number of damaged buildings by construction type at different seismic stations (source: Bijukchhen, et al., 2017)

It should be noted that the Gorkha earthquake was rather unusual in terms of frequency content, with relatively low spectral acceleration in the range of high-frequencies. This frequency interval covers most of the low-rise building stock in both the urban and rural areas, which led to surprisingly low damage. Based on past events with similar magnitude and seismogenic depth, the extent of the damage could have been much higher.

2.2. Floods

Nepal is considered the second highest country at risk of floods in the South Asia region (UNDP, 2009). Frequent floods, usually in the monsoon season, result in significant loss of life, property and livelihoods (Nepal Climate Vulnerability Study Team - NCVST 2009). Between 1954 and 2018, floods in Nepal caused 7,599 deaths, affected 6.1 million people and caused economic losses of about 10.6 billion USD. On average, 100 people were killed annually (EMDAT, 2019). The 1993 floods in Central Nepal, 2008 Koshi embankment breach floods, and the 2013, 2014 and 2017 floods in the mid- and far-western regions caused not only immense loss to both human life and property but also had a devastating impact on development.

Table 2.4: Flood damage and loss data from 1945 to 2018. Main sources of data are EMDAT and DesInventar.

Year	Total deaths	Injured	Affected	Houses Destroyed	Houses Damaged	Total damage ('000 USD)
1954	60					
1968	276		1,000			300
1970	350		20,000			
1971	34	1	810	31	19	600
1972	5	0	500	12	0	0
1973	23	0	7,200	285	66	0
1974	71	8	15,965	1,615	706	37,396.01
1975	15	0	6,663	69	3	8,570
1976	0	0	900	47	433	0
1977	17	0	1,008	55	275	11,000
1978	130	48	27,748	1,371	5	513
1979	15	2	51,738	711	0	20,500
1980	8	0	1,780	622	122	0
1981	750		10,000	632	796	
1982	92			46	21	
1983	186	50	200,050	63	1,092	10,000
1984	200			646	6	
1985	46	57	62,557	157	5	
1986	22			6	0	
1987	188		351,000	32	5,902	95,490
1988	27			264	13	
1989	31	3	12,328	330	1,200	626,614.75
1990	30		2,500	860	1,307	
1991	51	32	482	38	12	
1992	2	0	0	2	0	0
1993	1,048	268	553,268	15,164	18,726	200,000
1994	9	7	1,631	24	0	23,930
1995	140		13,000	3,626	14,250	1,200
1996	788	132	152,382	9,250	10,581	
1997	54	6	21,949	703	586	528,058.34
1998	310		70,000	12,731	437	27,000
1999	170	68	18,068	1,424	384	2,000
2000	144	70	50,070	1,770	876	6,300

2001	49	23	47,540	2,862	969	1,419,818.9
2002	133	118	378,361	11,323	4,675	6,886,633.8
2003	239	284	59,254	527	271	
2004	185	15	800,015	496	2,256	
2005	51		31,600	113	43	
2006				910	8,098	
2007	214	48	640,706	8,693	1,120	2,400
2008	115	3	250,003	12,950	1,643	29
2009	117	62	257,786	415	3,494	60,000
2010	150		8,000	2,513	5,731	
2011	104	32	1,858	2,777	3,909	
2012	72	5	5	123	5,983	1,000
2013	195	35	16,823	130	7,303	
2014	318	149	187,294			
2016	163	74	20,574			15,000
2017	187	134	1706,134	3,392	33,479	595,000
2018	15	6	1406			
TOTAL	**7,599**	**1,740**	**6,061,956**	**99,810**	**136,797**	**10,579,353.8**

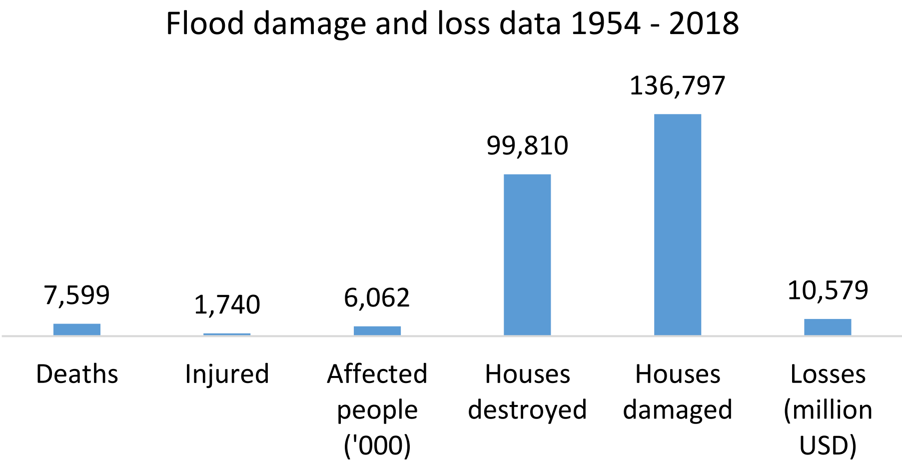


Figure 2.6: Summary of flood damage and loss data from EMDAT and DesInventar.

2.2.1. 2017 Nepal Floods

Heavy rains started in 11th August across the south of Chure hills and continued for several days resulting in widespread flooding across the Terai region. The heavy downpour resulted in series of flash floods in all the monsoon streams that drain through the hills in Terai. The Kankai River basin, Wes Rapti River basin, Karnali River basin swelled up exceeding the pre-defined warning threshold. Within 24 hours, rainfall depth had surpassed 200mm in several meteorological stations across the country (Bhandari, *et al.,* 2018). The floods resulted in 134 deaths, of which 44 were females as described in Table 2.5. About 190,000 houses suffered complete or partial damage resulting in the displacement of thousands of people and rendering many more homeless (PFRNA, 2017). Table 2.6 provides a detailed report of damage and loss of four communities reported by Bhandari, *et al.,* (2018).

District	Death		Injured		Affected Population
	Male	Female	Male	Female	
Banke	3	5	0	0	52,437
Bara	2	1	1	0	13,563
Bardiya	3	1	4	2	134,804
Chitwan	3	2	0	0	22,310
Dang	5	2	2	1	4,220
Dhanusha	3	0	0	1	68,970
Jhapa	11	5	0	0	24,980
Kailali	0	1	0	0	15,435
Mahottari	6	3	0	0	200,000
Makwanpur	4	3	2	2	11,080
Morang	11	5	1	0	23,577
Nawalparasi	2	0	0	0	6,450
Parsa	5	1	0	0	40,070
Rautahat	13	5	0	2	266,486
Saptari	4	0	0	0	648,945
Sarlahi	11	2	0	0	21,640
Siraha	0	0	0	0	58,300
Sunsari	4	8	3	1	75,207
TOTAL	**90**	**44**	**13**	**9**	**1,688,474**

Table 2.5: Number of deaths, injured and affected population in the several affected districts (source: PFRNA, 2017).

Community	Fatalities	Completely damage HH	Partially damaged HH	Loss (USD)
Karnali	0	7	234	13 M
Babai	4	2,273	16,906	21 M
West Rapti	8	1,071	15,737	-
Kankai	11	41	602	-

Table 2.6: Summary of damage and loss of four communities most affected by the floods (source: Bhandari, et al., 2018)

2.2.2. 1993 Floods of Bagamati River

The southern plains of Nepal were hit by one of the worst rain-induced floods in the country's history. On 20th July 1993, the Bagmati River barrage was disrupted sending about a 20-40 ft high wall of water crushing through the communities around the river and the extensive irrigation canal system. The floodwaters receded rapidly, and left thousands of people devastated. Early reports indicated 744 people were dead while more than 859 people were missing (Pradhan, *et al.,* 2007). A post flood survey classified households based on their socio-economic status as low, middle and high. The results showed that 72% of the households in affected communities were in thatch construction, 26% in wood and 2% in cement or brick (see Table 2.7).

House	Low	Middle	High	Total
Thatch	4,114	1,008	86	5,200
Wood/Tin	938	813	31	1,882
Cement or brick	78	53	31	162
TOTAL	**5,130**	**1,874**	**248**	**7,252**

Table 2.7: Distribution of households affected by the 1993 flood according to house construction material and by socio-economic level (source: Pradhan, et al., 2007).

Table 2.8 presents the extent of flood damage to the households. About 20% of the houses were considered severely damaged with 10% being washed away entirely and 8.9% becoming uninhabitable. 80% of the houses were habitable though with significant damage to its content. The type of construction greatly influenced the extent of damage; 22.3% of thatch houses were either washed away completely or uninhabitable, while only 10.3% and 7.4% of wood/tin and cement/brick houses were heavily damaged, respectively.

	House construction type			
Flood damage	**Thatch**	**Wood/Tin**	**Cement/ Brick**	**Total**
Washed away	647	71	8	726
Uninhabitable	517	123	4	644
Habitable	2,106	704	51	2,861
No damage	1,908	967	98	2,973
Other	30	17	1	48
TOTAL	**5,208**	**1,882**	**162**	**7,252**

Table 2.8: Degree of damage incurred by construction material (source: Pradhan, et al., 2007).

Extent of flood damage showed a positive correlation with social economic status of households. Buildings of households with low socio-economic status were completely washed away or significantly damaged such that it became uninhabitable as compared to households of middle and high socio-economic status. Table 2.9 shows the extent of damage suffered by households in each socio-economic class.

	Socio-economic class			
Flood damage	**Low %**	**Middle %**	**High %**	**Total**
Washed away	12.4	4.7	0.4	10.0
Uninhabitable	10.2	5.9	4.0	8.9
Habitable	39.1	40.7	36.7	39.5
Not damaged	37.6	48.1	58.1	41.0
Other	0.6	0.7	0.8	0.7
TOTAL	**100.0**	**100.0**	**100.0**	**100.0**

Table 2.9: Extent of damage suffered by households in each socio-economic class (source: Pradhan, et al., 2007).

Socio-Economic class	Low	Middle	High
	393	75	5
House type	**Thatch**	**Wood/Tin**	**Cement/Brick**
	413	57	3

Table 2.10: Number of deaths according to socio-economic class and construction type (source: Pradhan, et al., 2007).

2.3. Landslides

Landslides, which causes high levels of economic losses and fatalities every year, are a major constraint on development in Nepal. The geomorphology, seismic activity, intensity of monsoon rainfall and haphazard construction activities has made Nepal susceptible to landslide hazard. Rain induced landslide is the most common type of disaster and usually occurs in the monsoon period. Figure 2.7 presents a summary of historical damage and loss until 2017. Table 2.11 is a complete list of major landslides that resulted in significant damage and loss. Data presented herein were obtained from EMDAT and DesInventar.

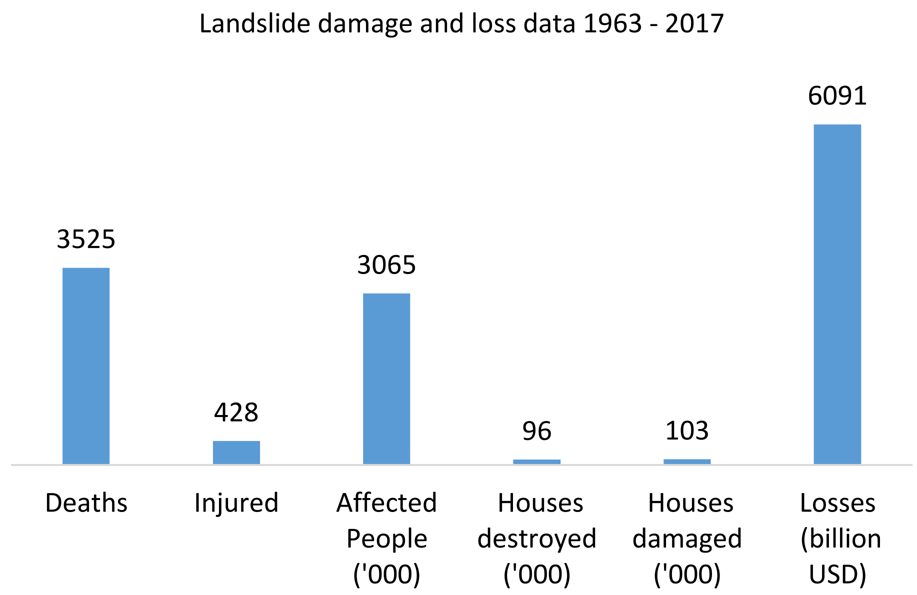


Figure 2.7: Historical landslide and damage data as obtained from EMDAT and DesInventar.

Year	Death	Injured	Affected People	Houses destroyed	Houses damaged	Losses ('000 USD)
1963	150					
1970	21					
1971	34	1	810	31	19	60
1972	105			12	0	0
1973	23	0	7,200	285	66	0
1974	71	8	15,965	1,615	706	3,740
1975	125		75,000	69	3	857

1976	150			47	433	0
1977	17	0	1,008	55	275	1,100
1978	10	2	10,509	1,371	5	2,723
1979	15	2	51,738	711	0	2,050
1980	8	0	1,780	622	122	0
1981	130	5	42,418	632	796	80
1982	3	0	564	46	21	630
1983	21			63	1,092	150
1984	167	3	2,521	646	6	1,108
1985	35	7	1,148	157	5	16
1986	8	0	0	6		25,680
1987	38	3	1,994	32	5,902	2,500
1988	10	0	1,313	264	13	7,531
1989	49			330	1,200	62,661
1990	52	0	2,072	860	1,307	600
1991	45	0	34,670	38	12	321
1992	2	0	0	2	0	0
1993	28		200	15,164	18,726	1,007,299
1994	9	7	1,631	24	0	2,393
1995	85	19	534	3,626	14,250	371,904
1996	73	8	374,425	9,250	10,581	140,330
1997	20			703	586	52,806
1998	131	53	468,724	12,731	437	188,323
1999	139	23	33,461	1,424	384	77,933
2000	79	13	18,824	1,770	876	626,340
2001	144		21,019	2,862	969	141,982
2002	472	105	265,865	11,323	4,675	688,663
2003	64	17	334,968	527	271	120,161
2004	77	5	263,688	496	2,256	130,300
2005	14	1	11,332	113	43	5,456
2006	157		80,000	910	8,098	44,780
2007	47	51	53,805	8,693	1,120	275,645
2008	127	15	194,506	12,950	1,643	1,489,036
2009	10			415	3,494	25,828
2010	136	36	157,396	2,513	5,731	433,361
2011	29			2,777	3,909	57,101
2012	111	7	459,366	123	5,983	36,000
2013	52	1	66,921	130	7,303	48,646
2014	156		476			15,000
2015	65	36	36			
2017	11		7,500			
TOTAL	**3,525**	**428**	**3,065,387**	**96,418**	**103,318**	**6,091,094**

Table 2.11: Landslide damage and loss data from 1954 – 2018. Data sources include EMDAT and DesInventar.

2.3.1. 2014 Landslide

A major landslide struck Nepal on 2nd August 2014 in a densely populated area northeast of Kathmandu in the Jure, Sindhupalchok district. The Landslide was 1.26 km long and 0.81 km wide, it blocked the Sunkoshi River and created a dam. It resulted in 156 fatalities and was considered as one of the deadliest landslides in the history of Nepal. It caused severe damage to houses, properties, infrastructure, farms and a hydropower plant. The Araniko Highway which connects Nepal to China was severely damaged resulting in severe impact on the Nepalese economy (Van der Geest and Schindler 2016).

2.3.2. 2015 Gorkha Landslide

Following the earthquake of 25th April, detailed satellite mapping and subsequent field observations revealed that about 25,000 landslides occurred (Zekkos, *et al.,* 2017). The landslides were primarily rockslides, rock falls and soil slope failure. In general, landslides occurred by gravitationally driven movement of material with falling, toppling, sliding, spreading, or flowing. In Nepal, the highest landslide densities overall (including pre-earthquake landslides) lay in the area between the epicenters of the three >M7.0 earthquakes of 26th August 1833, 25th April 2015, and 12th May 2015, highlighting the possible long term effects of historic earthquakes (Kargel, *et al.,* 2016), while the highest density of earthquake-induced landslides lay in a broad swath between the two largest shocks. Figure 2.8 depicts the inventory of landslides for 17 selected districts, which were surveyed following the ground shaking. The landslides resulted in significant loss to both life and property and affected the livelihood of the population in the mountainous regions.

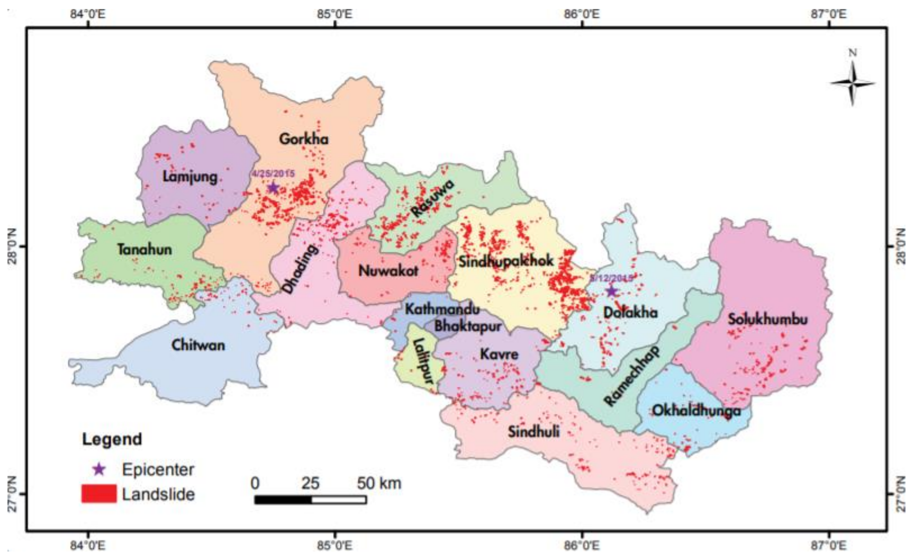


Figure 2.8: Landslide inventory of selected surveyed districts (Sheresta, et al., 2016).

Results of a field survey covering seven districts (Dhading, Dolakha, Gorkha, Nuwakot, Ramechhap, Rasuwa, and Sindhupalchok,) indicated that several households were affected, especially in the mountainous areas. The earthquake and its secondary geohazards affected several sectors of the economy. The destruction was widespread, covering residential and government buildings, heritage sites, schools and health posts, rural roads, bridges, water supply systems, agricultural land, trekking routes, and hydropower plants (Sheresta, *et al.,* 2016). The data showed that in these districts close to 9% of households were affected by geohazards in the form of landslides and debris flows (Table 2.12).

District	Households affected	Deaths	Loss USD (housing)	Loss USD (infrastructure)
Dhading	2,982	3	0	2,451
Dolakha	3,427	0	0	980
Gorkha	4,340	3	0	1,176
Nuwakot	-	1	3,922	17,745
Ramechap	-	0	0	27,941
Rasuwa	1,135	0	0	16,569
Sindhupalchok	1,135	30	68,627	303,333

Table 2.12: Damage and loss data for households affected by the 2015 earthquake-induced landslide in Nepal. Results for selected affected areas in seven districts (source: Sheresta, et al., 2016).

3. Past Disasters in Tanzania

Tanzania, like many other east African countries is prone to natural hazards such as floods, droughts, earthquakes, landslides, volcanoes and their secondary impacts (e.g. diseases and epidemics). Disasters have caused many deaths, rendered thousands homeless and affected millions of Tanzanians. The country has suffered major events such as the 2016 earthquake which killed more than 20 people (IFRCRCS, 2016) and resulted in losses exceeding USD400M (EMDAT, 2019). Flash floods can be considered as an annual peril in Tanzania. Almost every year, heavy rains cause flooding in many parts of the country, especially in the cities as a result of an increase in slums and poor urban plaining. Table 3.1 is showing fatalities, affected population and economic losses from recurrent natural hazards in Tanzania from 1900 – 2019 (EMDAT, 2019).

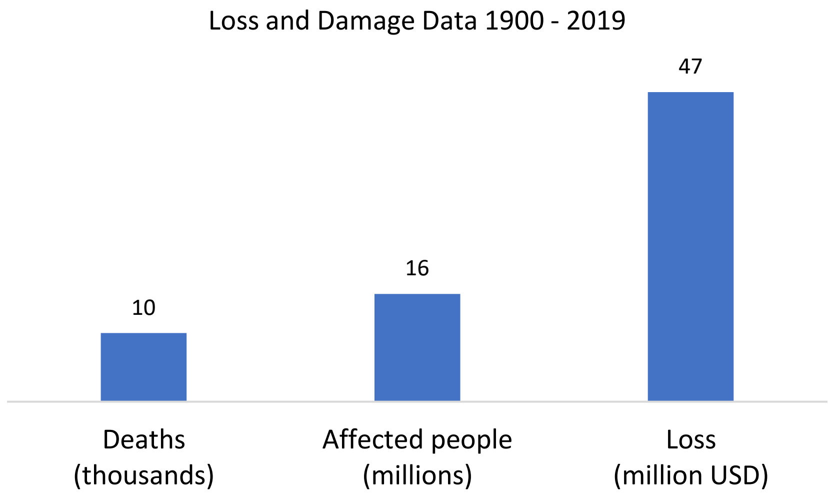


Figure 3.1: Impact of Natural hazards in Tanzania from 1900 -2019 (source: EMDAT).

In Tanzania, the disaster risk management comes directly under the office of the Prime Minister. There is no publicly available database of disaster damage or loss data to enable the understanding and calibration of damage functions for reliable loss estimates. Damage and loss data presented herein are for three perils: earthquakes, flood and volcanoes. The source of the data includes EMDAT, DesInventar, news websites, scientific publications and reports of relief organisations.

3.1. Earthquakes

Earthquakes remain one of the major natural perils in Tanzania, besides the frequent floods and long-lasting droughts that affect the country. The deadliest event in terms of impact happened in 2016, which killed more than 17 people, completely ruined close to 1,000 buildings and caused significant damage in about 1,200 houses. Figure 3.2 shows unreinforced masonry buildings and adobe houses that suffered complete damage during the 2016 earthquake. The following tables present earthquake damage and loss information from EMDAT (Table 3.1), NOAA (Table 3.2) and DesInventar (Table 3.3).


Figure 3.2: Brick Masonry (left) and adobe mud block (right) building which suffered complete damage during the 2016 earthquake (AFP 2011).

Year	Deaths	Injured	Total affected	Losses ('000 USD)
1901				
1908				
1910				
1913				
1964	4		500	
2000	1	6	791	
2001			700	
2002	2		2,000	
2004	10			
2005	2		5,000	
2016	17	440	139,601	458,000

Table 3.1: Earthquake damage and loss data for Tanzania (source EMDAT).

Year	Name	Mag	Deaths	Injuries	Houses destroyed	Houses damaged	Damage (million USD)
1964	Tanzania	6	1	19			
2000	Nkansi, Rukwa	6.5		1	1	3	1
2002	Nkansi, Rukwa	5.5	2		690	700	
2016	Lake Victoria	5.9	23	252	1,172	6,281	458
2017	Mwanza	4.4	1	18			
2019	Songwe, Mbeya	5.5	1		4		

Table 3.2: Earthquake damage and loss data for Tanzania (source: NOAA).

Year	Deaths	Injured	Houses Destroyed	Houses Damaged	Affected
1964	4				500
2001			7	148	7,086
2002	2	5	690	636	7,956
2016	17	560	2,072	24,056	
2017	1	2			

Table 3.3: Earthquake damage and loss data for Tanzania (source: DesInventar).

3.3. Floods

Floods continue to pose significant risk to several people in Tanzania. Building damage and loss data due to severe floods are imperative to calibrate fragility functions for proper risk assessment and loss estimation. Table 3.4, Table 3.5 and Table 3.6 are damage and loss information from EMDAT, DesInventar and Flood Observatory respectively showing number of deaths, injuries, affected people, complete and partial damage to buildings and the resulting economic losses due to flood events.

Year	Deaths	Injured	Affected	Losses ('000 USD)
1964			13,900	
1968	40		57,000	1,000
1974	25		68,000	3,000
1978			9,000	
1979			90,000	
1982			40,000	
1986			6,000	
1988			6,500	
1989	10		141,056	
1990	189		162,868	280
1993	54	30	201,823	3,510
1994	31		7,000	
1995	3		21,850	
1997	83		10,132	
1998	61		4,600	
2000	36	17	1,817	
2001	5		200	
2002	9		1,200	
2003			2,000	
2005	1		10,548	
2006		28	21,528	
2008	73	15	9,457	
2009	38		50,000	
2011	37	200	65,976	
2012	10			
2014	31		40,000	2,000
2015	12		5,000	
2016	16		140,275	
2017	7			
2018	15	11	15,873	
TOTAL	**789**	**301**	**1,203,603**	**9,790**

Table 3.4: Flood damage and loss data for Tanzania (source: EMDAT).

Year	Deaths	Injured	Houses destroyed	Houses damaged	Affected	Losses ('000 USD)
1934					0	
1964					4,900	
1968					52,500	
1970					44,000	
1972					870	
1974					39,000	
1975			25		0	
1976			41		5,547	
1978					4,189	
1979					90,457	
1980					4,000	
1981					1,200	
1982					23,423	
1986					17,500	
1988					1,300	
1989	15				108,323	
1990					142,000	
1996					45	38,000
1997			8		300	18,000
1998	66				0	
2000	32		86	320	3,490	
2001	19	20		32	406	10,553.5
2002				20	165	6,200
2008	74				0	
2009	2			5,981	25,637	
2011	41			677	11,643	
2013				200	1,000	
2014	10			127	0	
2015	16				0	
2016	3		315	802	5,862	
2017	17	56	445	915	3,908	
2018	9		529	2,736	19,876	
TOTAL	**304**	**76**	**1,449**	**11,810**	**611,541**	**72,753.5**

Table 3.5: Flood damage and loss data for Tanzania (source: DesInventar).

Began	Ended	Dead	Displaced	Main Cause	Severity
17/12/1989	25/12/1989	1	0	Heavy rain	1
3/4/1990	1/5/1990	100	4100,000	Heavy rain	2
8/2/1993	12/2/1993	54	2,900	Heavy rain	1
9/1/1994	13/1/1994	31	7,000	Heavy rain	1
4/3/1995	10/3/1995	0	2,000	Heavy rain	1
27/5/1995	1/6/1995	4	20,000	Heavy rain	1
20/3/1997	15/4/1997	61	3,000	Heavy rain	1
20/12/1997	31/12/1997	38	104,000	Heavy rain	1
14/11/1997	28/11/1997	0	400	Heavy rain	1
27/4/1998	4/5/1998	5	4,600	Brief torrential rain	1
1/12/2000	31/12/2000	3,600	0	Heavy rain	1
20/1/2001	20/1/2001	13	120	Heavy rain	1
27/2/2001	27/2/2001	7	0	Brief torrential rain	1
20/12/2003	21/12/2003	0	2,000	Heavy rain	1
2/2/2004	4/2/2004	4	0	Heavy rain	1
18/4/2004	19/4/2004	0	2,600	Heavy rain	1
16/4/2005	18/4/2005	1	300	Heavy rain	1
3/2/2006	12/2/2006	1	938	Heavy rain	1
9/5/2006	17/5/2006	0	19,000	Heavy rain	1
11/4/2008	16/5/2008	0	800	Heavy rain	1
10/11/2009	13/11/2009	20	0	Heavy Rain	1
25/12/2009	27/12/2009	1	3,000	Heavy Rain	1
9/4/2011	19/5/2011	8	9,000	Heavy Rain	1.5
20/12/2011	22/12/2011	13	0	Heavy Rain	2
1/3/2012	7/3/2012	10	0	Heavy Rain	1
13/5/2012	16/5/2012	0	300	Heavy Rain	1
18/4/2014	1/5/2014	41	0	Torrential Rain	1.5
10/5/2014	16/5/2014	0	22,000	Heavy Rain	1
3/3/2015	23/3/2015	38	0	Torrential Rain	1.5
7/5/2015	21/5/2015	12	5,000	Heavy Rain	1.5
14/1/2016	29/1/2016	1	400	Heavy Rain	1
22/4/2016	30/5/2016	5	14,000	Heavy Rain	1.5
14/4/2018	17/4/2018	9	0	Heavy Rain	1

Table 3.6: Flood damage and loss data for Tanzania (source: Flood Observatory, Colorado).

3.4. Volcanoes

Brown et al. (2015) provide a comprehensive overview of the volcanic hazard in Tanzania. Ten Holocene volcanoes are known to exist in Tanzania in two distinct clusters. One cluster in the north of the country includes Mount Meru, Mount Kilimanjaro, and Ol Doinyo Lengai. The southern cluster includes Mount Rungwe, Mount Kyejo (Kieyo), Mount Ngozi, Igwisi Hills, Izumbwe-Mpoli, Usangu Basin, and an as-yet unnamed volcano. A few volcanoes in Kenya are situated within 100 km of the border with Tanzania.

Figure 2.1, from Brown et al. (2015), shows the geographical location of these volcanoes within and around Tanzania. Nearly 7 million people, around 16.4% of Tanzania's population lives within 100 km distance from a Holocene volcano (see Table 3.7, from Brown et al., 2015). Table 3.8 shows the dates of the last known confirmed eruptions of the Holocene volcanoes in Tanzania.

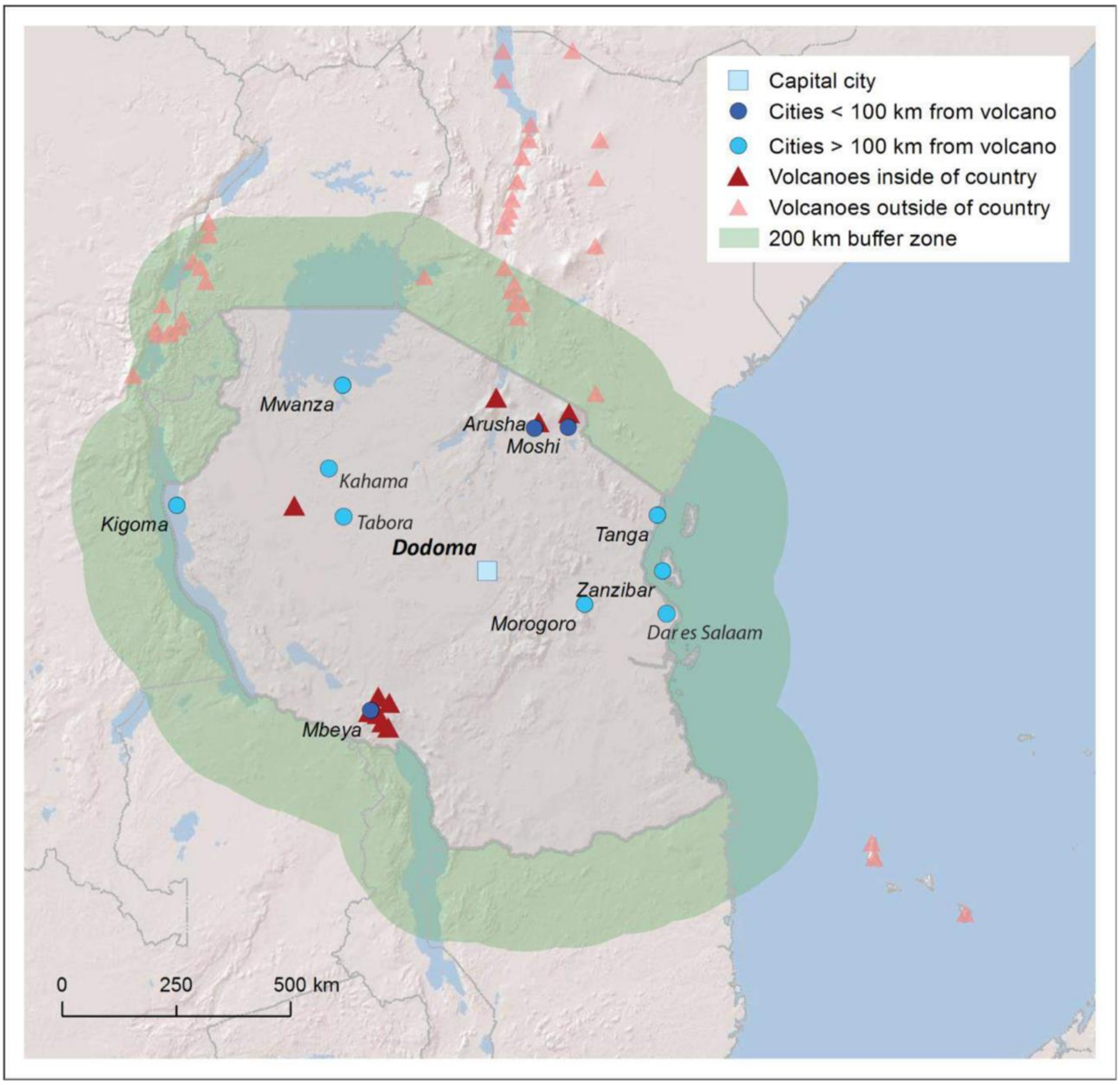


Figure 3.3. Volcanoes in and around Tanzania. Figure source: Brown et al., 2015.

Ol Doinyo Lengai has erupted several times in the past century, typically with effusive to moderately explosive activity (Global Volcanism Program, 2013 [Ol Doinyo Lengai, Volcano Number 222120]). Table 3.9 shows the dates of confirmed eruptions of this volcano, and the Volcanic Explosivity Index (VEI) where available. Rungwe, Meru, and Ngozi have had large (VEI ≥ 4) eruptions in the Holocene. Table 3.10 provides the approximate dates and VEI for these events. Shompole, which lies on the Tanzania–Kenya border, is not considered to be an active volcano, but there have been records of increased seismicity in the area surrounding this volcano (Brown et al., 2015).

Table 3.7. Population exposure in the vicinity of Holocene volcanoes in Tanzania. Source: Brown et al., 2015

Exposure Criteria	Number of People	Percentage of Tanzania's Population
Within 10 km of a Holocene volcano	532,918	1.3%
Within 30 km of a Holocene volcano	2,604,862	6.1%
Within 100 km of a Holocene volcano	6,997,614	16.4%

Table 3.8. Last known eruption years for Holocene volcanoes in Tanzania. Source: Global Volcanism Program, 2013.

Volcano Name	Summit Elevation	Primary Volcano Type	Last Known Eruption
Ol Doinyo Lengai	2,962 m	Stratovolcano	2019 CE
Meru	4,565 m	Stratovolcano	1910 CE
Kyejo	2,176 m	Stratovolcano	1800 CE
Ngozi	2,614 m	Caldera	1450 CE
Runqwe	2,953 m	Stratovolcano	1250 CE
Igwisi Hills	1,146 m	Pyroclastic Cone	10450 BCE

Table 3.9. VEI of confirmed eruptions of Ol Doinyo Lengai since 1916. Source: Global Volcanism Program, 2013 [Ol Doinyo Lengai (Volcano Number 222120)].

Eruption Start Date	Eruption Stop Date	VEI
2017 Apr 9	2019 Jun 18 (continuing)	
2016 Sep 21 (in or before)	2016 Oct 13 (in or after)	
2015 Jun 20 (in or before)	2015 Aug 24 (in or after)	
2011 Jun 22 (in or before)	2014 Jul 15 ± 10 days	
2007 Jun 16 ± 15 days	2010 Oct 9 (?) ± 1 days	3
1994 Sep 18	2006 Jul 16 (?) ± 15 days	1
1983 Jan 1	1993 Sep 24	2
1967 Jul 8	1967 Sep 4	3
1960 Mar 16 (in or before) ± 15 days	1966 Nov 28 ± 30 days	3
1958 Feb 6 (in or before)	Unknown	1
1955 Jan 19	1955 Jan 20	2
1954 Jul 26 ± 5 days	1954 Sep 16 ± 15 days	2
1940 Jul 24	1941 Feb	3
1926	Unknown	2
1921 Feb	Unknown	2
1916 Dec 1 ± 30 days	1917 Jun	3

In recorded history, only one volcano eruption in Tanzania is known to have caused fatalities. Lava flows from the 1800 eruption of Kyejo caused 15 deaths (Brown et al., 2017). In addition, Brown et al. (2015) indicate that injuries and loss of livestock were reported during the 2007 Ol Doinyo Lengai eruption.

Loughlin et al. (2015) provide estimates of average recurrence intervals for explosive eruptions of volcanoes around the world. The average recurrence intervals for volcanoes in Tanzania from Loughlin et al. (2015) are listed in Table 3.11.

Table 3.10. Holocene volcano eruptions in Tanzania with VEI ≥ 4. Source: Global Volcanism Program, 2013.

Volcano Name	Eruption Date	VEI
Rungwe	0050 BCE ± 100 years	4
Rungwe	2050 BCE (?)	5
Meru	5850 BCE (?)	4
Ngozi	8250 BCE (?)	5

Table 3.11. Average recurrence intervals for explosive eruptions of volcanoes in Tanzania. Source: Loughlin et al., 2015.

Volcano Name	Average Recurrence Intervals for Explosive Eruptions (Years)					
	Any VEI	VEI ≤ 3	VEI 4	VEI 5	VEI 6	VEI 7
Ol Doinyo Lengai	14	15	195	680	2,830	3,020
Meru	96	105	1,370	4,790	19,900	21,300
Kyejo	215	235	3,040	10,700	44,400	47,300
Ngozi	570	670	7,110	14,200	28,400	118,500
Runqwe	645	710	9,210	32,200	134,300	143,200

The paucity of monitoring systems near Tanzania’s active volcanoes and scarcity of written historical records could mean that the likelihood of future eruptions might be underestimated (Brown et al., 2015).

4. Selection of Fragility and Vulnerability: Introduction

The assessment of the potential impact due to natural hazards requires the definition of a fragility or vulnerability model. The former component establishes the probability of exceeding a set of damage states conditional on an intensity measure level (e.g. ground shaking intensity, water depth, ashfall thickness, permanent ground deformation). An example of a fragility function is presented in Figure 4.1.

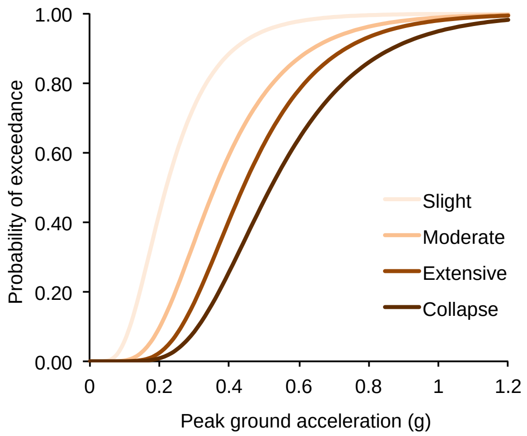


Figure 4.1: Example of a fragility function in terms of peak ground acceleration. Such function can be used to assess damage due to earthquakes for a particular building class.

Fragility functions can be combined with a damage-to-loss model to produce a vulnerability function. A damage-to-loss model defines the fraction of loss for a number of damage states. For example, in the United States it is common to assume that a building with slight damage will need 10% of its economic value to be repaired. In Africa and South-East Asia, a building with extensive damage or complete damage will most likely be demolished, thus losing 100% of its value. A vulnerability function defines the relation between the probability of loss ratio, and an intensity measure level, as illustrated in Figure 4.2.

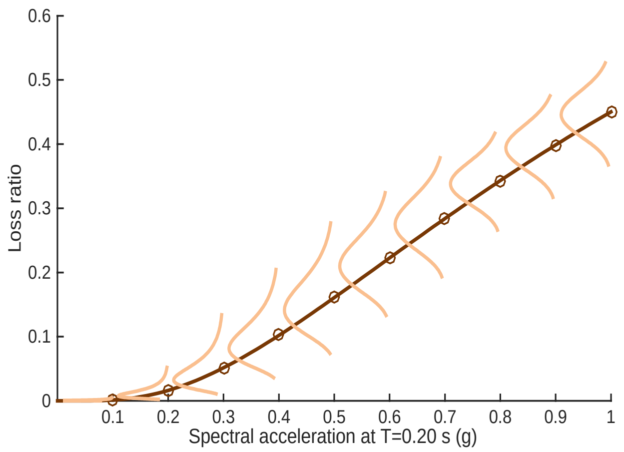


Figure 4.2: Example of a fragility function in terms of peak ground acceleration. Such function can be used to assess damage due to earthquakes for a particular building class.

The vulnerability component is of particular importance in disaster risk reduction, as the improvement of the seismic performance of the assets at risk may lead to a direct reduction of the likelihood of loss or damage, thus effectively reducing the potential for economic or human losses. For example, in Nepal several schools have been structurally retrofitted in Kathmandu before the 2015 M7.8 Gorkha earthquake, and performed remarkably well during this seismic event.

The development of fragility or vulnerability curves may involve the manipulation of large datasets, the use of expert elicitation, the development of computationally demanding numerical models, and the performance of complex statistical analysis, which may require advanced expertise in the various fields of structural engineering and numerical modelling. These are some of the reasons for the strong paucity of fragility and vulnerability functions worldwide, and in particular for less developed nations where usually only the hazard component, and less frequently also the exposure component, is readily available. It is thus fundamental to leverage upon the wealth of existing functions that have been developed over the last decades by numerous experts.

The Global Earthquake Model Foundation has made available an online platform which promotes the dissemination of existing models, accessible at: https://platform.openquake.org. More recently, the Global Facility for Disaster Reduction and Recovery (GFDRR) of the World Bank also promoted the development of a platform to disseminate exposure datasets, hazard footprints and vulnerability models for a wide range of perils: http://assess-risk.info. The vulnerability taxonomy being used within the METEOR project follows closely these two efforts, thus ensuring that the outcomes of the project are compatible with existing dissemination platforms.

Fragility and vulnerability models can be derived using analytical, empirical and expert elicitation methodologies or a hybrid combination of these. The first approach relies on numerical models or analytical formulations to represent the structural capacity of the building classes. These numerical models are then tested against different levels of hazard severity. For example, earthquakes are usually represented by ground motion records (i.e. time histories of acceleration or displacement of the ground – Yepes et al. 2016). Floods and tsunamis are represented by the flow of water volumes or direct application of water pressure (e.g. Charvet et al. 2017). Landslides can be tested by either simulating the pressure of debris in the ground storey or by permanent deformations at the foundations (e.g. Fotopoulou and Pitilakis, 2013a). Volcanic ashfall can be simulated by applying increasing loads on the roof structure, as illustrated in Figure 4.3.

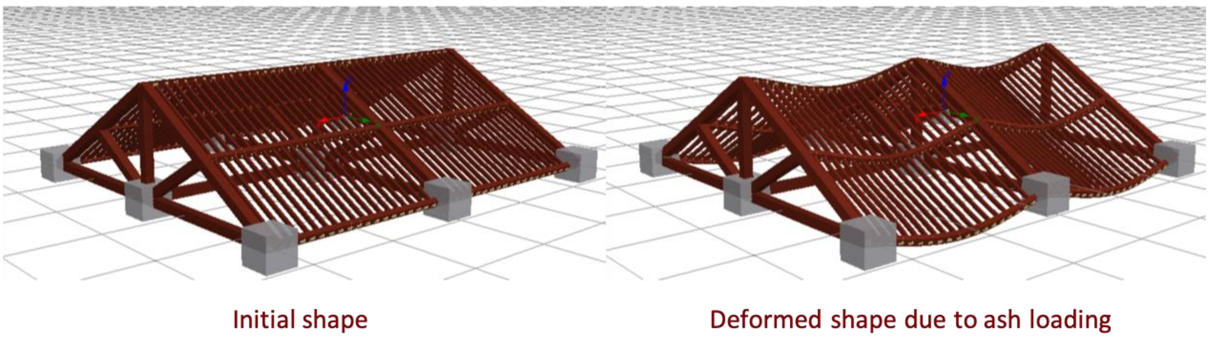


Figure 4.3: Numerical simulation of the deformation caused by ashfall on a wooden roof in a typical building from Eastern Africa.

Analytical modelling has several advantages. It allows considering any building class (granted that the material, geometric and dynamic properties are available or can be estimated) and explicitly account for sources of uncertainties such as building-to-building variability and uncertaity in the hazard demand. For example, it is possible to numerically model many buildings (e.g. a set of existing buildings in downtown Kathmandu) and test them against a large number of ground motion records (for the particular case of earthquakes) or different landslide deformations. On the other hand, numerical simulations still have limitations related with the inability to properly model complex failure mechanisms, and it might require experimental tests to calibrate the various numerical elements. Figure 4.4 illustrates a numerical model for a typical reinforced concrete building in Nepal and the resulting fragility function for earthquakes. This particular phase of the numerical simulation shows the development of a failure mechanism in the ground floor.

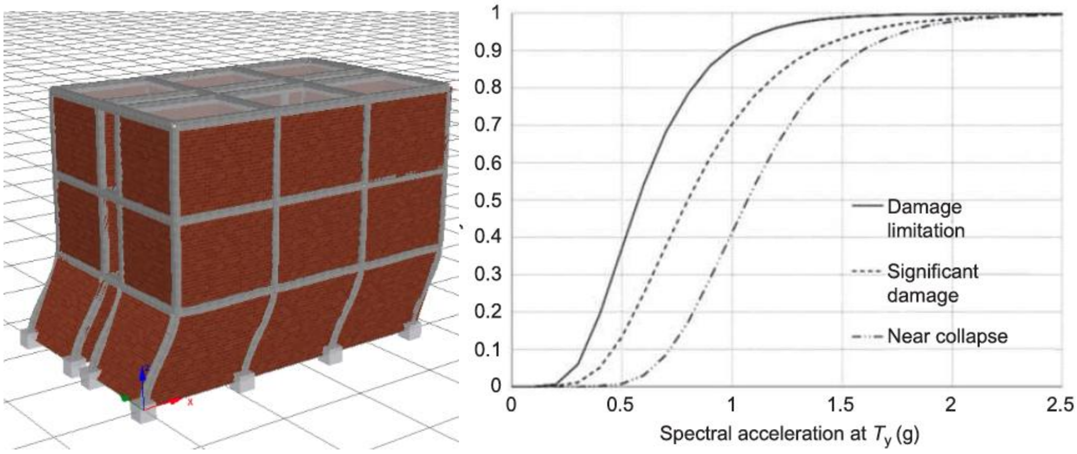


Figure 4.4: Numerical simulation of the deformation caused by ashfall on a wooden roof in a typical building from Eastern Africa.

Empirical methodologies are an excellent alternative to overcome some of the limitations of analytical modelling. In this approach, statistical regression analyses are applied to damage or loss data to derive sets of fragility or vulnerability functions (e.g. Colombi et al. 2008). In theory, an empirical approach is the most realistic method to derive a fragility or vulnerability models, given that it is based on actual damage or loss on existing structures (and thus it considers all of the peculiarities of the built environment, such as structural deficiencies, state of conservation, dependency between assets) caused by a hazard demand that considered all of the peculiarities of a given event (e.g. topography, wind velocity, geology, energy released). However, there are a number of limitations that add uncertainty and bias in an empirical approach. In particular, the damage classification can be a subjective process, which depends on the expertise of the surveyor and familiarity with the local construction practices. The definition of the hazard demand can also be a challenging task, in particular for storms and earthquakes, for which the absence of a monitoring or recording station will leave modellers with no option but to estimate the hazard severity at the location of the damaged assets with experimental or analytical models. An example of an empirical fragility function that illustrates issues due to the inability to constrain the hazard demand is presented in Figure 4.5. In this example, some of the fragility curves cross each other, while others are relatively "flat". This is an indication of a poor correlation between the evolution of damage and the increase in the hazard severity. This is a common issue observed when the hazard demand at the location of the affected assets is unknown and have to be analytically or experimentally estimated.

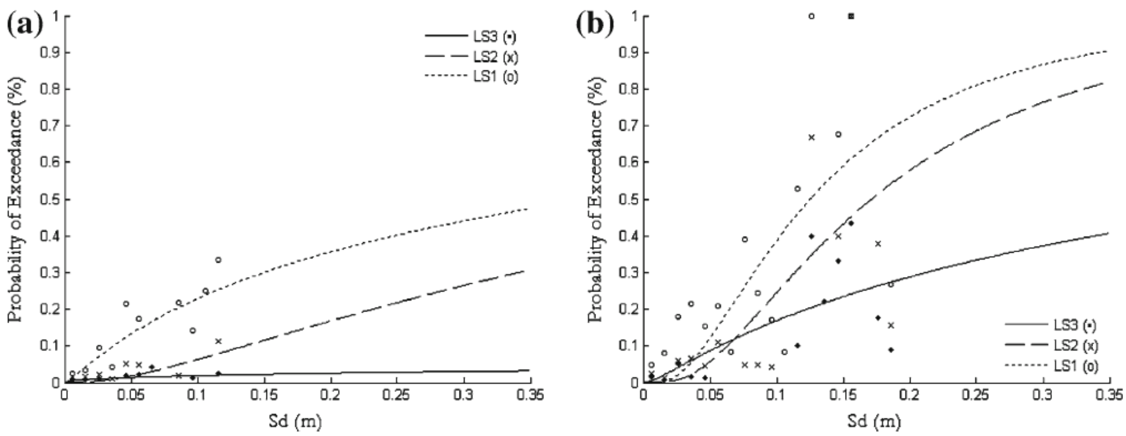


Figure 4.5: Fragility functions derived using an empirical approach using damage data for Italy due to earthquakes. (a) represents reinforced concrete buildings with 1-2 storey while (b) represents the same type of construction but with 3-5 storeys. The damage criterion adopted 3 damage states: LS1 - slight damage, LS2 – significant damage and LS3 - collapse.

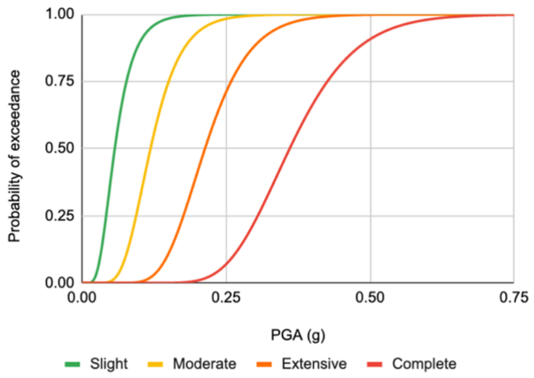
Finally, it is also worth mentioning that empirical approaches require large amounts of data in order to generate unbiased fragility functions, which are obviously resource and time-demanding. Moreover, such approach might be impractical in regions where destructive earthquakes do not happen frequently, such as Tanzania.

Fragility curves can also be derived based on the elicitation and pooling of the subjective opinion of a large group of experts (e.g. ATC-13 1985; Jaiswal et al. 2012). These are often termed judgement-based fragility curves. This approach has the advantage of being relatively expedite and allowing to cover a large number of building classes, but naturally the results can be characterized by a large subjectivity. A combination of two or more of these approaches is also possible (i.e. the hybrid method), where for example, empirical damage data is used to calibrate analytically derived fragility curves (e.g. Singhal and Kiremidjian 1997), or numerical models are used to predict the expected distribution of damage or loss for levels of hazard for which no empirical damage data is available (e.g. Kappos et al. 2006). In the vast majority of existing fragility curves, a cumulative lognormal distribution function (parameterized by a logarithmic mean and standard deviation) is employed to represent the probability of exceeding each damage state as a function of the hazard demand. Vulnerability functions usually do not follow a particular parametric distribution, and are instead define by a discrete model (i.e. set of loss ratios for a set of hazard intensity level).

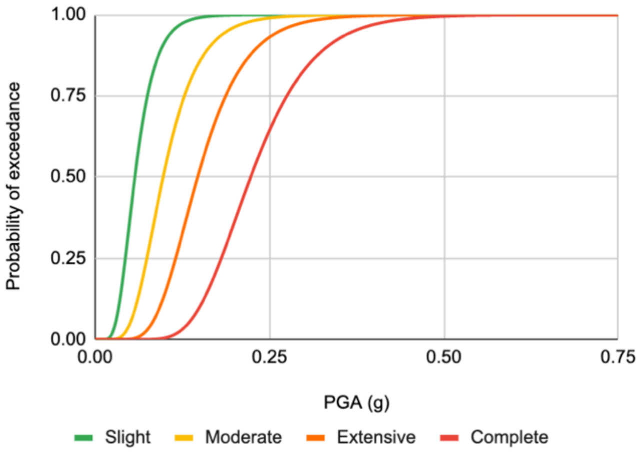
Within the METEOR project, hundreds of fragility functions have been collected and reviewed for the four natural hazards (earthquakes, landslides, floods and volcanic ashfall). From this pool of functions, a reduced number of functions was selected based on the types of construction found in Tanzania and Nepal (in agreement with the finding from Work Package 3 and 4 of the project), reliability of the methodology and whether any verification or testing had been performed. Section 5 presents the selected functions following the vulnerability taxonomy defined in Deliverable 5.1 (Definition of taxonomy for multi-peril vulnerability).

5. Fragility and Vulnerability Functions for Nepal

5.1. Fragility functions for earthquake hazard

ID: EQ-BL-FF (Guragain 2015)	
Hazard	Earthquake
Asset	Building
Taxonomy	MUR+MOC
Typology of Structure	Brick in cement buildings with flexible floor/roof
Country ISO	NPL
Approach	Analytical nonlinear dynamic analysis
References	Guragain, R. (2015). *Development of seismic risk assessment system for Nepal*. PhD dissertation. http://doi.org/10.15083/00007589.
Figures	
Variables	**IM: PGA** **Damage States** / **µ** / **σ** Slight 0.057 0.451 Moderate 0.119 0.349 Extensive 0.214 0.286 Complete 0.361 0.247
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Peak ground acceleration (g)
Uncertainties	Uncertainty in the hazard is considered through analysis of multiple ground motion records.
Comments	Guragain 2015 proposes two sets of fragility curves for each building typology and indicates that these indicate lower and upper bounds. The set of parameters presented here are selected to go between the bounds presented by Guragain 2015.

<table>
<tr><td colspan="2">ID: EQ-BL-FF (Guragain 2015)</td></tr>
<tr><td>Hazard</td><td>Earthquake</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+MOM</td></tr>
<tr><td>Typology of Structure</td><td>Brick in mud buildings with flexible floor/roof</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical nonlinear dynamic analysis</td></tr>
<tr><td>References</td><td>Guragain, R. (2015). Development of seismic risk assessment system for Nepal. PhD dissertation. http://doi.org/10.15083/00007589.</td></tr>
<tr><td>Figures</td><td>



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<tr><td>Extensive</td><td>0.147</td><td>0.358</td></tr>
<tr><td>Complete</td><td>0.223</td><td>0.310</td></tr>
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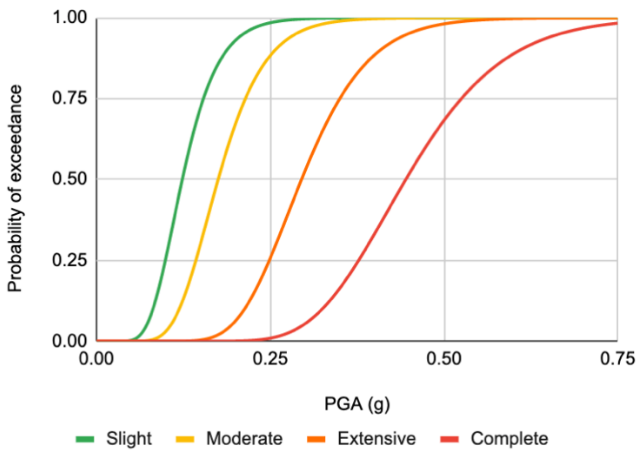
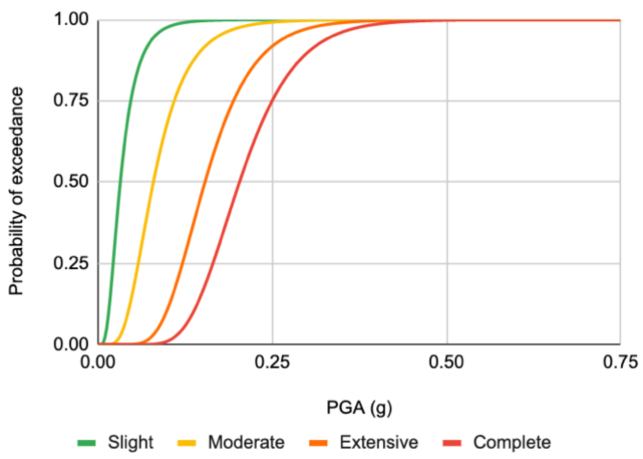
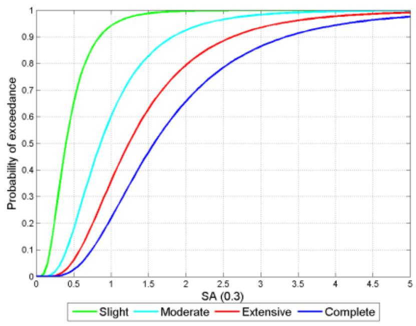
</td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>DS1: Slight damage
DS2: Moderate damage
DS3: Extensive damage
DS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>Peak ground acceleration (g)</td></tr>
<tr><td>Uncertainties</td><td>Uncertainty in the hazard is considered through analysis of multiple ground motion records.</td></tr>
<tr><td>Comments</td><td>Guragain 2015 proposes two sets of fragility curves for each building typology and indicates that these indicate lower and upper bounds. The set of parameters presented here are selected to go between the bounds presented by Guragain 2015.</td></tr>
</table>

ID: EQ-BL-FF (Guragain 2015)	
Hazard	Earthquake
Asset	Building
Taxonomy	MUR+MOC
Typology of Structure	Brick in cement buildings with rigid floor/roof
Country ISO	NPL
Approach	Analytical nonlinear dynamic analysis
References	Guragain, R. (2015). *Development of seismic risk assessment system for Nepal*. PhD dissertation. http://doi.org/10.15083/00007589.
Figures	
Variables	**IM: PGA** **Damage States** / **μ** / **σ** Slight 0.124 0.326 Moderate 0.175 0.300 Extensive 0.295 0.254 Complete 0.445 0.245
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Peak ground acceleration (g)
Uncertainties	Uncertainty in the hazard is considered through analysis of multiple ground motion records.
Comments	Guragain 2015 proposes two sets of fragility curves for each building typology and indicates that these indicate lower and upper bounds. The set of parameters presented here are selected to go between the bounds presented by Guragain 2015.

IM: PGA		
Damage States	**μ**	**σ**
Slight	0.124	0.326
Moderate	0.175	0.300
Extensive	0.295	0.254
Complete	0.445	0.245

ID: EQ-BL-FF (Guragain 2015)	
Hazard	Earthquake
Asset	Building
Taxonomy	MUR+ST+MOC
Typology of Structure	Brick in cement buildings with flexible floor/roof, stone masonry
Country ISO	NPL
Approach	Analytical nonlinear dynamic analysis
References	Guragain, R. (2015). *Development of seismic risk assessment system for Nepal*. PhD dissertation. http://doi.org/10.15083/00007589.
Figures	
Variables	**IM: PGA** **Damage States** / **μ** / **σ** Slight / 0.032 / 0.571 Moderate / 0.080 / 0.474 Extensive / 0.154 / 0.350 Complete / 0.203 / 0.308
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Peak ground acceleration (g)
Uncertainties	Uncertainty in the hazard is considered through analysis of multiple ground motion records.
Comments	Guragain 2015 proposes two sets of fragility curves for each building typology and indicates that these indicate lower and upper bounds. The set of parameters presented here are selected to go between the bounds presented by Guragain 2015.

ID: EQ-BL-FF-GEM-2019	
Hazard	Earthquake
Asset	Building
Taxonomy	MUR+ADO+MON
Typology of Structure	Unreinforced masonry bearing wall structure. Material technology: Adobe without mortar
Country ISO	NPL
Approach	Analytical nonlinear dynamic analysis
References	GEM global vulnerability and fragility database
Figures	
Variables	**IM: SA(0.3)** **Damage States** · **μ** · **σ** Slight · 0.399 · 0.586 Moderate · 0.861 · 0.586 Extensive · 1.238 · 0.586 Complete · 1.577 · 0.586
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Spectral acceleration (g)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.
Comments	These functions have been tested in probabilistic seismic risk assessment for Nepal.

<table>
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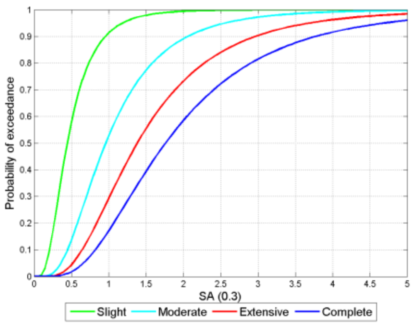
<tr><td>Hazard</td><td>Earthquake</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+STRUB+MON</td></tr>
<tr><td>Typology of Structure</td><td>Unreinforced masonry bearing wall structure. Material technology: Rubble stone without mortar</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical nonlinear dynamic analysis</td></tr>
<tr><td>References</td><td>GEM global vulnerability and fragility database</td></tr>
<tr><td>Figures</td><td>
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<tr><th>Damage States</th><th>μ</th><th>σ</th></tr>
<tr><td>Slight</td><td>0.445</td><td>0.595</td></tr>
<tr><td>Moderate</td><td>0.9609</td><td>0.595</td></tr>
<tr><td>Extensive</td><td>1.3834</td><td>0.595</td></tr>
<tr><td>Complete</td><td>1.7618</td><td>0.595</td></tr>
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<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>DS1: Slight damage
DS2: Moderate damage
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<tr><td>Uncertainties</td><td>The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.</td></tr>
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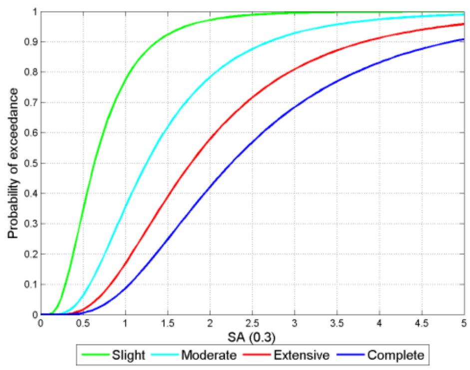
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+CLBRS+MOM</td></tr>
<tr><td>Typology of Structure</td><td>Unreinforced masonry bearing wall structures. Material technology: Fired clay bricks with mud mortar</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical nonlinear dynamic analysis</td></tr>
<tr><td>References</td><td>GEM global vulnerability and fragility database</td></tr>
<tr><td>Figures</td><td>
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<tr><td>Damage state names</td><td>DS1: Slight damage
DS2: Moderate damage
DS3: Extensive damage
DS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>Spectral acceleration (g)</td></tr>
<tr><td>Uncertainties</td><td>The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.</td></tr>
<tr><td>Comments</td><td>These functions have been tested in probabilistic seismic risk assessment for Nepal.</td></tr>
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<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+STRUB+MOM</td></tr>
<tr><td>Typology of Structure</td><td>Unreinforced masonry bearing wall structure. Material technology: Rubble stone with mud mortar</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
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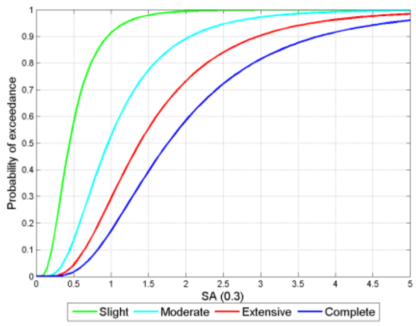
<tr><td>Figures</td><td>
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<tr><td>Slight</td><td>0.445</td><td>0.595</td></tr>
<tr><td>Moderate</td><td>0.9609</td><td>0.595</td></tr>
<tr><td>Extensive</td><td>1.3834</td><td>0.595</td></tr>
<tr><td>Complete</td><td>1.7618</td><td>0.595</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>DS1: Slight damage
DS2: Moderate damage
DS3: Extensive damage
DS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>Spectral acceleration (g)</td></tr>
<tr><td>Uncertainties</td><td>The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.</td></tr>
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<tr><td>Hazard</td><td>Earthquake</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+CBS+MOC</td></tr>
<tr><td>Typology of Structure</td><td>Unreinforced masonry bearing wall structure. Material technology: Concrete blocks with cement mortar</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical nonlinear dynamic analysis</td></tr>
<tr><td>References</td><td>GEM global vulnerability and fragility database</td></tr>
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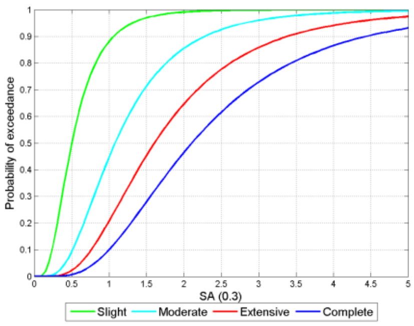

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DS2: Moderate damage
DS3: Extensive damage
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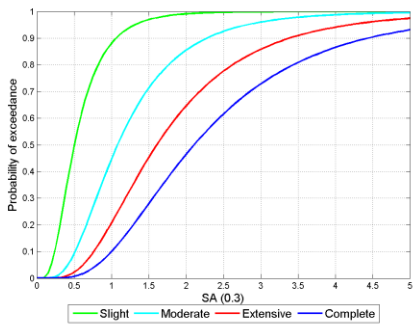
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+CLBRS+MOC</td></tr>
<tr><td>Typology of Structure</td><td>Unreinforced masonry bearing wall structure. Material technology: Fired clay bricks with cement mortar</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical nonlinear dynamic analysis</td></tr>
<tr><td>References</td><td>GEM global vulnerability and fragility database</td></tr>
<tr><td>Figures</td><td>
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<tr><td>Variables</td><td>IM: SA(0.3)
Damage States | μ | σ
Slight | 0.5043 | 0.581
Moderate | 1.0820 | 0.581
Extensive | 1.6088 | 0.581
Complete | 2.1073 | 0.581</td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>DS1: Slight damage
DS2: Moderate damage
DS3: Extensive damage
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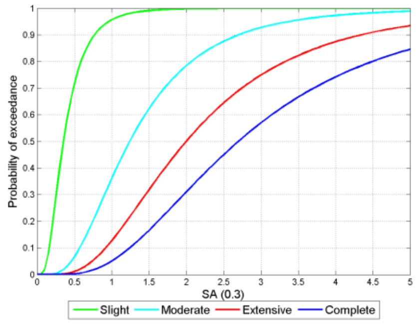
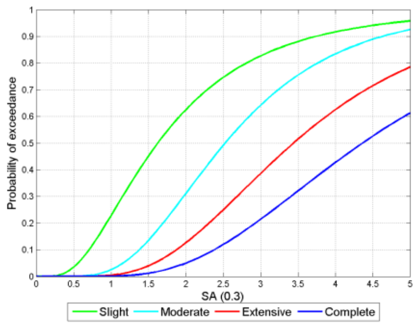
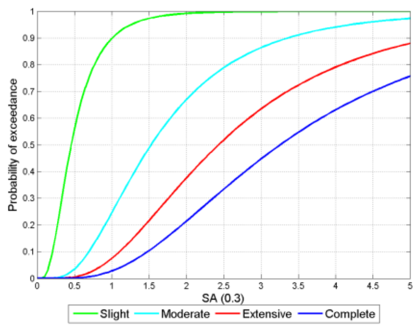
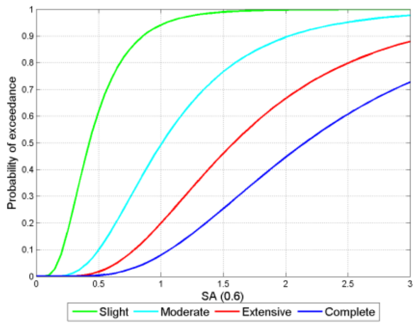
<tr><td>Intensity measure name</td><td>Spectral acceleration (g)</td></tr>
<tr><td>Uncertainties</td><td>The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.</td></tr>
<tr><td>Comments</td><td>These functions have been tested in probabilistic seismic risk assessment for Nepal.</td></tr>
</table>

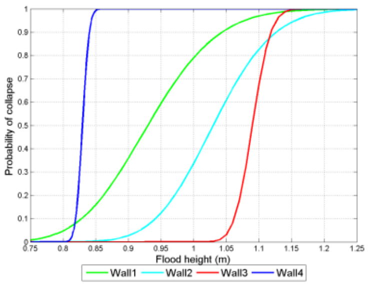
ID: EQ-BL-FF-GEM-2019	
Hazard	Earthquake
Asset	Building
Taxonomy	W+WWB
Typology of Structure	Non-engineered wooden structure. Material technology: bamboo
Country ISO	NPL
Approach	Analytical nonlinear dynamic analysis
References	GEM global vulnerability and fragility database
Figures	
Variables	**IM: SA(0.3)** **Damage States** / **μ** / **σ** Slight / 0.3532 / 0.606 Moderate / 1.2400 / 0.606 Extensive / 1.9970 / 0.606 Complete / 2.6975 / 0.606
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Spectral acceleration (g)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.
Comments	These functions have been tested in probabilistic seismic risk assessment for Nepal.

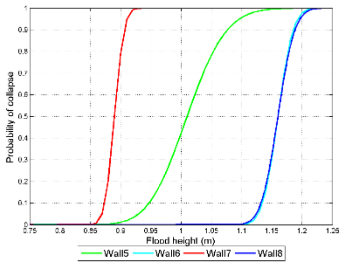
ID: EQ-BL-FF-GEM-2019	
Hazard	Earthquake
Asset	Building
Taxonomy	W+WLI
Typology of Structure	Non-engineered wooden structure. Material technology: light wood members
Country ISO	NPL
Approach	Analytical nonlinear dynamic analysis
References	GEM global vulnerability and fragility database
Figures	
Variables	**IM: SA(0.3)** **Damage States** / **μ** / **σ** Slight 1.6261 0.473 Moderate 2.5263 0.473 Extensive 3.4401 0.473 Complete 4.3638 0.473
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Spectral acceleration (g)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.
Comments	These functions have been tested in probabilistic seismic risk assessment for Nepal.

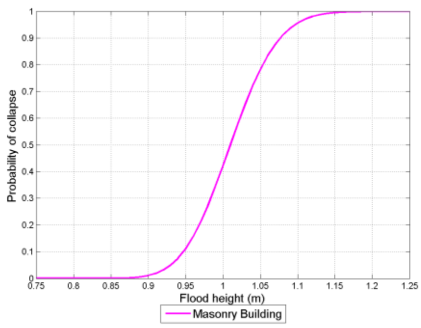
ID: EQ-BL-FF-GEM-2019	
Hazard	Earthquake
Asset	Building
Taxonomy	CR/LFINF
Typology of Structure	Infilled frame concrete reinforced structure
Country ISO	NPL
Approach	Analytical nonlinear dynamic analysis
References	GEM global vulnerability and fragility database
Figures	
Variables	**IM: SA(0.3)** **Damage States** / **μ** / **σ** Slight 0.4579 0.615 Moderate 1.5283 0.615 Extensive 2.4308 0.615 Complete 3.2585 0.615
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Spectral acceleration (g)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.
Comments	These functions have been tested in probabilistic seismic risk assessment for Nepal.

ID: EQ-BL-FF-GEM-2019	
Hazard	Earthquake
Asset	Building
Taxonomy	CR/LFM
Typology of Structure	Moment frame concrete reinforced structure
Country ISO	NPL
Approach	Analytical nonlinear dynamic analysis
References	GEM global vulnerability and fragility database
Figures	
Variables	**IM: SA(0.3)** **Damage States** — **µ** — **σ** Slight — 0.4579 — 0.545 Moderate — 1.5283 — 0.545 Extensive — 2.4308 — 0.545 Complete — 3.2585 — 0.545
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Spectral acceleration (g)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.
Comments	These functions have been tested in probabilistic seismic risk assessment for Nepal.

5.2. Fragility functions for floods

ID: FL-BL-FF (Jalayer *et al.,* 2016)	
Hazard	Flood
Asset	Building
Taxonomy	MUR+CLBRS, MUR+CBS, MCF
Typology of Structure	Non engineered regular masonry with cement blocks/bricks
Country ISO	NPL
Approach	Analytical
References	Jalayer, F., Carozza, S., De Risi, R., Manfredi, G. & Mbuya, E. (2016). Performance-Based Flood Safety-Checking for Non-Engineered Masonry Structures. Engineering Structures 106: 109–23. http://dx.doi.org/10.1016/j.engstruct.2015.10.007.
Figures	
Variables	**IM: Flood height (m)** **Cases** / **Median** / **σ** Wall 1 / 0.93 / 0.09 Wall 2 / 1.03 / 0.03 Wall 3 / 1.09 / 0.02 Wall 4 / 0.83 / 0.01
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	***Collapse damage state conditioned on different sides of the walls of varying factored critical flooding height*** Wall 1 Wall 2 Wall 3 Wall 4
Intensity measure name	Flood height (m)
Uncertainties	The structural fragility was calculated taking into account the uncertainty in loading and material properties and by using an efficient Bayesian procedure providing a robust fragility curve and its plus/minus one standard deviation confidence interval.
Comments	

<table>
<tr><td colspan="2">ID: FL-BL-FF-(Jalayer et al., 2016)</td></tr>
<tr><td>Hazard</td><td>Flood</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+CLBRS, MUR+CBS, MCF</td></tr>
<tr><td>Typology of Structure</td><td>Non engineered regular masonry with cement blocks</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Jalayer, F., Carozza, S., De Risi, R., Manfredi, G. & Mbuya, E. (2016). Performance-Based Flood Safety-Checking for Non-Engineered Masonry Structures. Engineering Structures 106: 109–23. http://dx.doi.org/10.1016/j.engstruct.2015.10.007.</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM: Flood height (m)</th></tr>
<tr><th>Cases</th><th>Median</th><th>σ</th></tr>
<tr><td>Wall 5</td><td>1.01</td><td>0.05</td></tr>
<tr><td>Wall 6</td><td>1.16</td><td>0.017</td></tr>
<tr><td>Wall 7</td><td>0.89</td><td>0.014</td></tr>
<tr><td>Wall 8</td><td>1.16</td><td>0.019</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>Collapse damage state conditioned on different sides of the walls of varying factored critical flooding height
Wall 5 Wall 6 Wall 7</td></tr>
<tr><td>Intensity measure name</td><td>Flood height (m)</td></tr>
<tr><td>Uncertainties</td><td>The structural fragility was calculated taking into account the uncertainty in loading and material properties and by using an efficient Bayesian procedure providing a robust fragility curve and its plus/minus one standard deviation confidence interval.</td></tr>
<tr><td>Comments</td><td></td></tr>
</table>

<table>
<tr><td colspan="2">ID: FL-BL-FF-(Jalayer et al., 2016)</td></tr>
<tr><td>Hazard</td><td>Flood</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+CLBRS, MUR+CBS, MCF</td></tr>
<tr><td>Typology of Structure</td><td>Non engineered regular masonry with cement blocks</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Jalayer, F., Carozza, S., De Risi, R., Manfredi, G. & Mbuya, E. (2016). Performance-Based Flood Safety-Checking for Non-Engineered Masonry Structures. Engineering Structures 106: 109–23. http://dx.doi.org/10.1016/j.engstruct.2015.10.007.</td></tr>
<tr><td>Figures</td><td>
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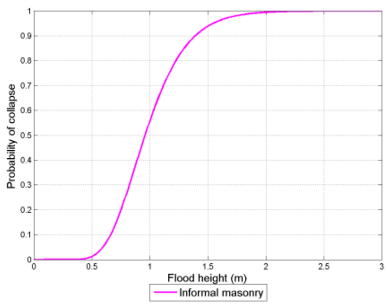
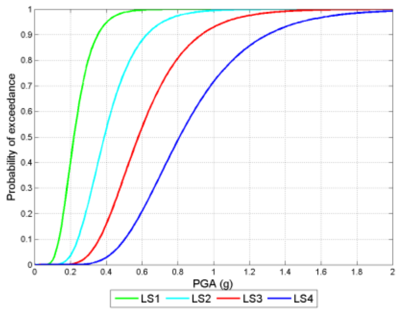
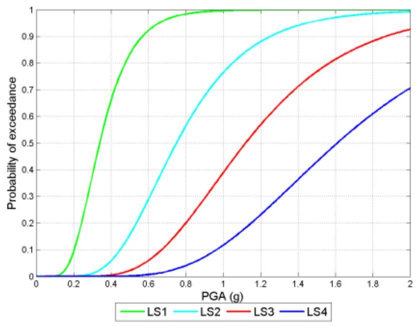
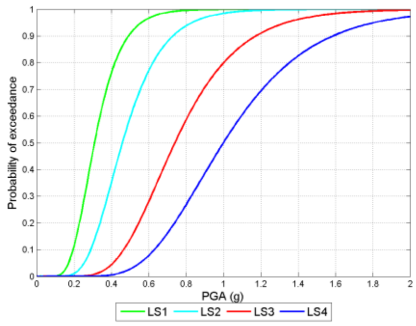
<tr><td>Variables</td><td><table><tr><td colspan="3">IM: Flood height (m)</td></tr><tr><td>Case</td><td>Median</td><td>σ</td></tr><tr><td>Entire building</td><td>0.83</td><td>0.015</td></tr></table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>Collapse damage state conditioned on entire performance of the building
Building</td></tr>
<tr><td>Intensity measure name</td><td>Flood height (m)</td></tr>
<tr><td>Uncertainties</td><td>The structural fragility was calculated taking into account the uncertainty in loading and material properties and by using an efficient Bayesian procedure providing a robust fragility curve and its plus/minus one standard deviation confidence interval.</td></tr>
<tr><td>Comments</td><td></td></tr>
</table>

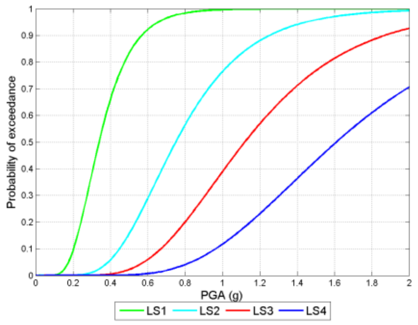
<table>
<tr><td colspan="2">ID: FL-BL-FF-(Risi et al., 2013)</td></tr>
<tr><td>Hazard</td><td>Flood</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+ADO, EU+ETR, MUR+CLRBS, MUR+CBS</td></tr>
<tr><td>Typology of Structure</td><td>Informal construction (Adobe, rammed earth or cement stabilized blocks) with corrugated iron sheets</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>De Risi R., Jalayer F., De Paola F., Iervolino I., Giugni M., Topa M. E., Mbuya E., Kyessi A., Manfredi G. & Gasparini P. (2013). Flood Risk Assessment for Informal Settlements. Natural Hazards 69(1): 1003–32. http://link.springer.com/10.1007/s11069-013-0749-0.</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM: Flood height (m)</th></tr>
<tr><th>Case</th><th>Median</th><th>σ</th></tr>
<tr><td>Building</td><td>0.9598</td><td>0.29</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>Collapse damage state</td></tr>
<tr><td>Intensity measure name</td><td>Flood height (m)</td></tr>
<tr><td>Uncertainties</td><td>The uncertainties taken into account in the assessment of structural vulnerability can be classified into those related to material and geometric properties.</td></tr>
<tr><td>Comments</td><td></td></tr>
</table>

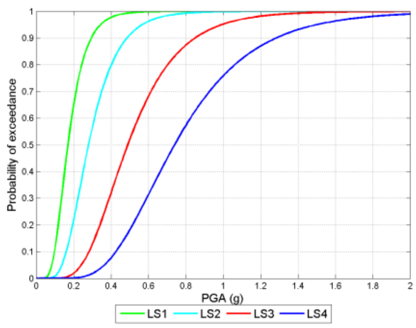
5.3. Landslide Fragility and Vulnerability Functions

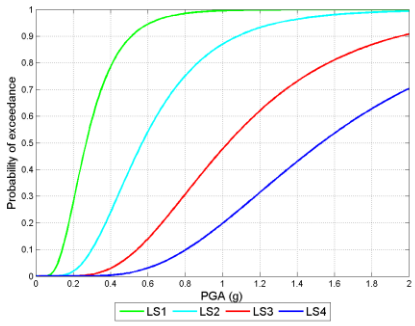
ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)	
Hazard	Landslide
Asset	Building
Taxonomy	CR/LFINF, LF/LFM
Typology of Structure	Single storey RC bare frame structure with flexible foundation system
Country ISO	NPL
Approach	Analytical
References	Fotopoulou, S.D. & Pitilakis, K.D. 2013. “Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides.” Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.
Figures	
Variables	**IM:PGA** **Damage state / Median / σ** LS1 / 0.22 / 0.37 LS2 / 0.39 / 0.37 LS3 / 0.58 / 0.37 LS4 / 0.81 / 0.37
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
Intensity measure name	PGA (g)
Uncertainties	Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure.
Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest.

<table>
<tr><td colspan="2">ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)</td></tr>
<tr><td>Hazard</td><td>Landslide</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>CR/LFINF, LF/LFM</td></tr>
<tr><td>Typology of Structure</td><td>Single storey RC bare frame structure with flexible foundation system</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM:PGA</th></tr>
<tr><th>Damage state</th><th>Median</th><th>σ</th></tr>
<tr><td>LS1</td><td>0.34</td><td>0.4</td></tr>
<tr><td>LS2</td><td>0.75</td><td>0.4</td></tr>
<tr><td>LS3</td><td>1.12</td><td>0.4</td></tr>
<tr><td>LS4</td><td>1.61</td><td>0.4</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>LS1: Slight damage, LS2: Moderate damage
LS3: Extensive damage, LS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>PGA (g)</td></tr>
<tr><td>Uncertainties</td><td>Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure</td></tr>
<tr><td>Comments</td><td>Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest.</td></tr>
</table>

ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)	
Hazard	Landslide
Asset	Building
Taxonomy	CR/LFINF, LF/LFM
Typology of Structure	Single storey RC bare frame structure with flexible foundation system
Country ISO	NPL
Approach	Analytical
References	Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.
Figures	
Variables	**IM:PGA** **Damage state** / **Median** / **σ** LS1 0.31 0.36 LS2 0.46 0.36 LS3 0.74 0.36 LS4 1.00 0.36
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
Intensity measure name	PGA (g)
Uncertainties	Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure
Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest

<table>
<tr><td colspan="2">ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)</td></tr>
<tr><td>Hazard</td><td>Landslide</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>CR/LFINF, LF/LFM</td></tr>
<tr><td>Typology of Structure</td><td>Single storey RC bare frame structure with flexible foundation system</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM:PGA</th></tr>
<tr><th>Damage state</th><th>Median</th><th>σ</th></tr>
<tr><td>LS1</td><td>0.34</td><td>0.4</td></tr>
<tr><td>LS2</td><td>0.75</td><td>0.4</td></tr>
<tr><td>LS3</td><td>1.12</td><td>0.4</td></tr>
<tr><td>LS4</td><td>1.61</td><td>0.4</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>LS1: Slight damage, LS2: Moderate damage
LS3: Extensive damage, LS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>PGA (g)</td></tr>
<tr><td>Uncertainties</td><td>Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure</td></tr>
<tr><td>Comments</td><td>Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest.</td></tr>
</table>

<table>
<tr><td colspan="2">ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)</td></tr>
<tr><td>Hazard</td><td>Landslide</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>CR/LFINF, LF/LFM</td></tr>
<tr><td>Typology of Structure</td><td>Single storey RC bare frame structure with flexible foundation system</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM:PGA</th></tr>
<tr><th>Damage state</th><th>Median</th><th>σ</th></tr>
<tr><td>LS1</td><td>0.17</td><td>0.43</td></tr>
<tr><td>LS2</td><td>0.28</td><td>0.43</td></tr>
<tr><td>LS3</td><td>0.49</td><td>0.43</td></tr>
<tr><td>LS4</td><td>0.74</td><td>0.43</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>LS1: Slight damage, LS2: Moderate damage
LS3: Extensive damage, LS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>PGA (g)</td></tr>
<tr><td>Uncertainties</td><td>Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure</td></tr>
<tr><td>Comments</td><td>Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest.</td></tr>
</table>

<table>
<tr><td colspan="2">ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)</td></tr>
<tr><td>Hazard</td><td>Landslide</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>CR/LFINF, LF/LFM</td></tr>
<tr><td>Typology of Structure</td><td>Single storey RC bare frame structure with flexible foundation system</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.</td></tr>
<tr><td>Figures</td><td>
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<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM:PGA</th></tr>
<tr><th>Damage state</th><th>Median</th><th>σ</th></tr>
<tr><td>LS1</td><td>0.27</td><td>0.5</td></tr>
<tr><td>LS2</td><td>0.57</td><td>0.5</td></tr>
<tr><td>LS3</td><td>1.03</td><td>0.5</td></tr>
<tr><td>LS4</td><td>1.53</td><td>0.5</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>LS1: Slight damage, LS2: Moderate damage
LS3: Extensive damage, LS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>PGA (g)</td></tr>
<tr><td>Uncertainties</td><td>Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure</td></tr>
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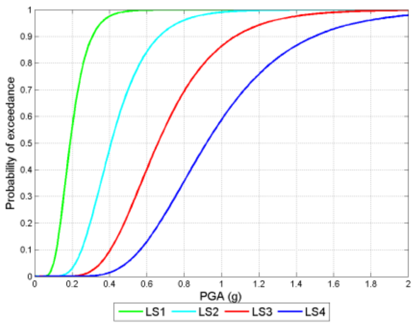
Hazard	Landslide
Asset	Building
Taxonomy	CR/LFINF, LF/LFM
Typology of Structure	Single storey RC bare frame structure with flexible foundation system
Country ISO	NPL
Approach	Analytical
References	Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.
Figures	
Variables	IM:PGA Damage state / Median / σ LS1 / 0.19 / 0.38 LS2 / 0.41 / 0.38 LS3 / 0.66 / 0.38 LS4 / 0.92 / 0.38
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
Intensity measure name	PGA (g)
Uncertainties	Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure
Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest

Variables (IM:PGA):

Damage state	Median	σ
LS1	0.19	0.38
LS2	0.41	0.38
LS3	0.66	0.38
LS4	0.92	0.38

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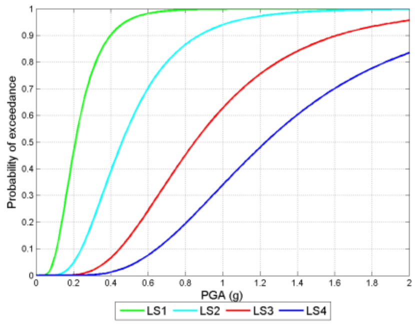
<tr><td>Figures</td><td>
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<tr><td>LS1</td><td>0.21</td><td>0.5</td></tr>
<tr><td>LS2</td><td>0.46</td><td>0.5</td></tr>
<tr><td>LS3</td><td>0.85</td><td>0.5</td></tr>
<tr><td>LS4</td><td>1.23</td><td>0.5</td></tr>
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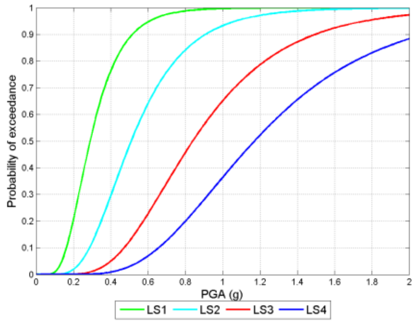

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<tr><td>Variables</td><td>
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<tr><th colspan="3">IM:PGA</th></tr>
<tr><th>Damage state</th><th>Median</th><th>σ</th></tr>
<tr><td>LS1</td><td>0.29</td><td>0.45</td></tr>
<tr><td>LS2</td><td>0.51</td><td>0.45</td></tr>
<tr><td>LS3</td><td>0.84</td><td>0.45</td></tr>
<tr><td>LS4</td><td>1.17</td><td>0.45</td></tr>
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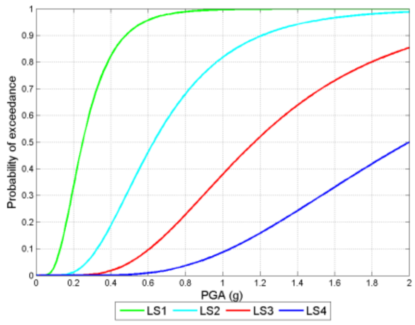
Figures	
Variables	**IM:PGA** **Damage state** / **Median** / **σ** LS1 0.25 0.51 LS2 0.63 0.51 LS3 1.17 0.51 LS4 2.00 0.51
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
Intensity measure name	PGA (g)
Uncertainties	Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure.
Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest.

Variables (IM:PGA)

Damage state	Median	σ
LS1	0.25	0.51
LS2	0.63	0.51
LS3	1.17	0.51
LS4	2.00	0.51

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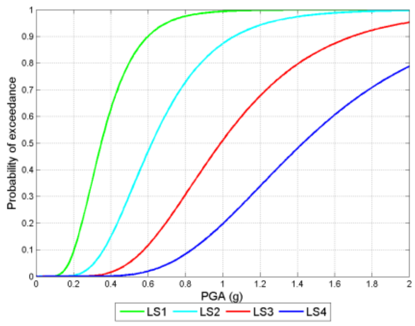
<tr><td>Figures</td><td>
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<tr><th colspan="3">IM:PGA</th></tr>
<tr><th>Damage state</th><th>Median</th><th>σ</th></tr>
<tr><td>LS1</td><td>0.35</td><td>0.42</td></tr>
<tr><td>LS2</td><td>0.62</td><td>0.42</td></tr>
<tr><td>LS3</td><td>0.99</td><td>0.42</td></tr>
<tr><td>LS4</td><td>1.43</td><td>0.42</td></tr>
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<tr><td>Damage state names</td><td>LS1: Slight damage, LS2: Moderate damage
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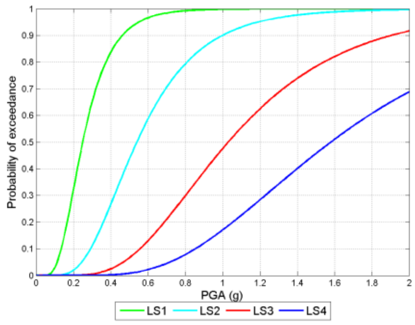
Figures	
Variables	**IM:PGA** **Damage state** / **Median** / **σ** LS1 / 0.25 / 0.48 LS2 / 0.54 / 0.48 LS3 / 1.03 / 0.48 LS4 / 1.58 / 0.48
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
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Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest.

IM:PGA		
Damage state	**Median**	**σ**
LS1	0.25	0.48
LS2	0.54	0.48
LS3	1.03	0.48
LS4	1.58	0.48

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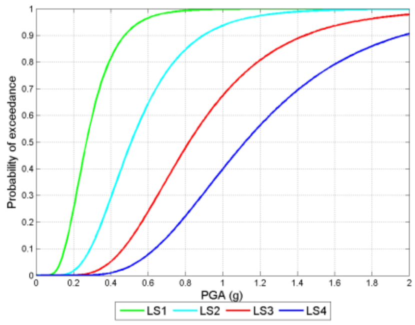

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<tr><th>Damage state</th><th>Median</th><th>σ</th></tr>
<tr><td>LS1</td><td>0.27</td><td>0.44</td></tr>
<tr><td>LS2</td><td>0.51</td><td>0.44</td></tr>
<tr><td>LS3</td><td>0.82</td><td>0.44</td></tr>
<tr><td>LS4</td><td>1.12</td><td>0.44</td></tr>
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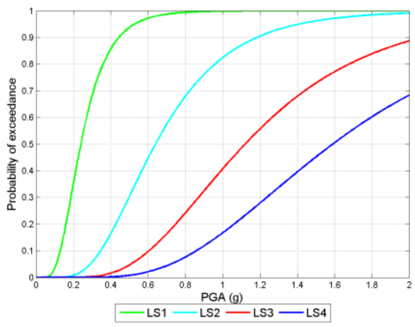
Figures	
Variables	**IM:PGA** **Damage state / Median / σ** LS1 / 0.24 / 0.48 LS2 / 0.64 / 0.48 LS3 / 1.12 / 0.48 LS4 / 1.59 / 0.48
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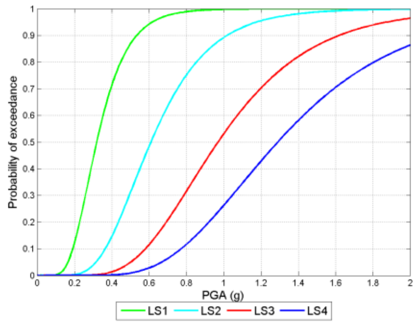
Figures	
Variables	**IM:PGA** **Damage state** / **Median** / **σ** LS1 0.32 0.4 LS2 0.61 0.4 LS3 0.97 0.4 LS4 1.29 0.4
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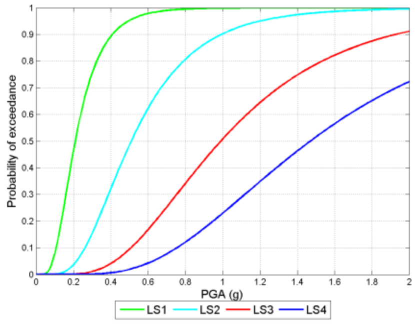
Figures	
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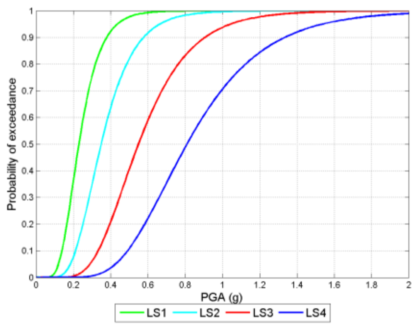
<tr><td>Figures</td><td>
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<tr><td>LS3</td><td>0.55</td><td>0.39</td></tr>
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Approach	Analytical
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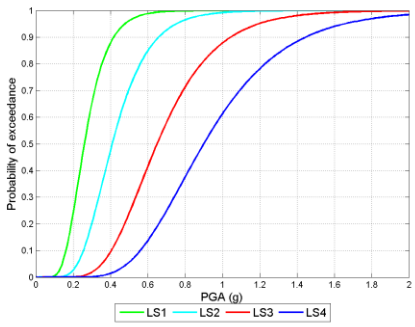
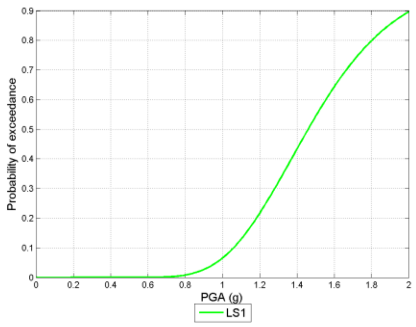
Figures	
Variables	IM:PGA **Damage state** / **Median** / **σ** LS1 / 0.26 / 0.37 LS2 / 0.41 / 0.37 LS3 / 0.65 / 0.37 LS4 / 0.9 / 0.37
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
Intensity measure name	PGA (g)
Uncertainties	Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure
Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest

<table>
<tr><td colspan="2">ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)</td></tr>
<tr><td>Hazard</td><td>Landslide</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>CR/LFINF, LF/LFM</td></tr>
<tr><td>Typology of Structure</td><td>Single storey RC bare frame structure with flexible foundation system</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.</td></tr>
<tr><td>Figures</td><td>
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<tr><td>Variables</td><td>
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<tr><td>LS1</td><td>1.46</td><td>0.25</td></tr>
<tr><td>LS2</td><td>–</td><td>0.25</td></tr>
<tr><td>LS3</td><td>–</td><td>0.25</td></tr>
<tr><td>LS4</td><td>–</td><td>0.25</td></tr>
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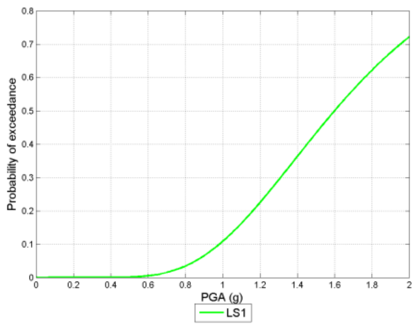
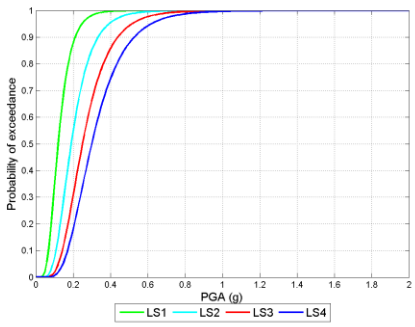
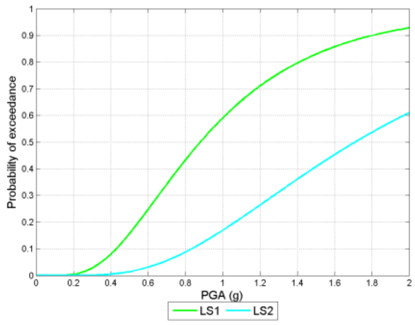
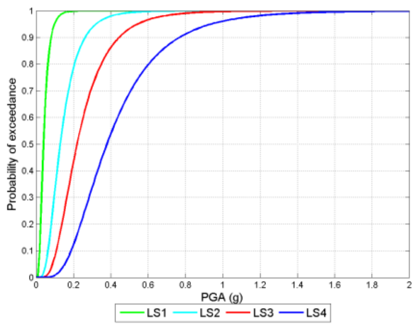
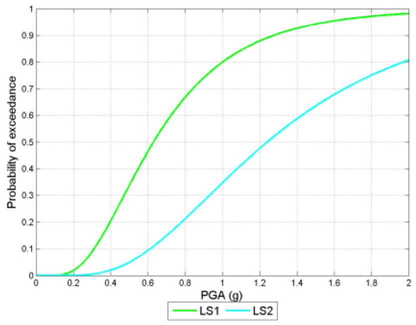
</td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>LS1: Slight damage, LS2: Moderate damage
LS3: Extensive damage, LS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>PGA (g)</td></tr>
<tr><td>Uncertainties</td><td>Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure</td></tr>
<tr><td>Comments</td><td>Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest</td></tr>
</table>

ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)	
Hazard	Landslide
Asset	Building
Taxonomy	CR/LFINF, LF/LFM
Typology of Structure	Single storey RC bare frame structure with flexible foundation system
Country ISO	NPL
Approach	Analytical
References	Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.
Figures	
Variables	**IM:PGA** **Damage state** / **Median** / **σ** LS1 / 1.6 / 0.38 LS2 / – / 0.38 LS3 / – / 0.38 LS4 / – / 0.38
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
Intensity measure name	PGA (g)
Uncertainties	Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure
Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest

ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)	
Hazard	Landslide
Asset	Building
Taxonomy	CR/LFINF, LF/LFM
Typology of Structure	Single storey RC bare frame structure with flexible foundation system
Country ISO	NPL
Approach	Analytical
References	Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.
Figures	
Variables	**IM:PGA** **Damage state** / **Median** / **σ** LS1 / 0.12 / 0.44 LS2 / 0.19 / 0.44 LS3 / 0.25 / 0.44 LS4 / 0.30 / 0.44
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
Intensity measure name	PGA (g)
Uncertainties	Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure
Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest

ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)	
Hazard	Landslide
Asset	Building
Taxonomy	CR/LFINF, LF/LFM
Typology of Structure	Single storey RC bare frame structure with flexible foundation system
Country ISO	NPL
Approach	Analytical
References	Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.
Figures	
Variables	**IM:PGA** **Damage state** / **Median** / **σ** LS1 / 0.88 / 0.56 LS2 / 1.71 / 0.56 LS3 / – / 0.56 LS4 / – / 0.56
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
Intensity measure name	PGA (g)
Uncertainties	Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure
Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest

ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)	
Hazard	Landslide
Asset	Building
Taxonomy	CR/LFINF, LF/LFM
Typology of Structure	Single storey RC bare frame structure with flexible foundation system
Country ISO	NPL
Approach	Analytical
References	Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.
Figures	
Variables	**IM:PGA** **Damage state** / **Median** / **σ** LS1 / 0.04 / 0.55 LS2 / 0.13 / 0.55 LS3 / 0.22 / 0.55 LS4 / 0.38 / 0.55
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	LS1: Slight damage, LS2: Moderate damage LS3: Extensive damage, LS4: Complete damage
Intensity measure name	PGA (g)
Uncertainties	Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure
Comments	Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest

<table>
<tr><td colspan="2">ID: LS-BL-FF-(Fotopoulou & Pitilakis, 2013)</td></tr>
<tr><td>Hazard</td><td>Landslide</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>CR/LFINF, LF/LFM</td></tr>
<tr><td>Typology of Structure</td><td>Single storey RC bare frame structure with flexible foundation system</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Fotopoulou, S.D. & Pitilakis, K.D. (2013). Fragility Curves for Reinforced Concrete Buildings to Seismically Triggered Slow-Moving Slides. Soil Dynamics and Earthquake Engineering 48: 143–61. http://dx.doi.org/10.1016/j.soildyn.2013.01.004.</td></tr>
<tr><td>Figures</td><td>
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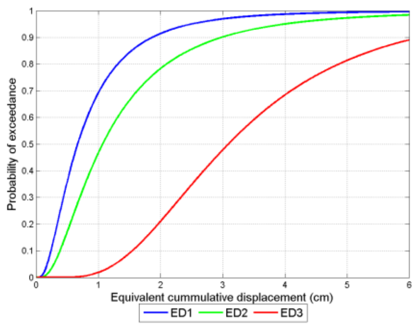
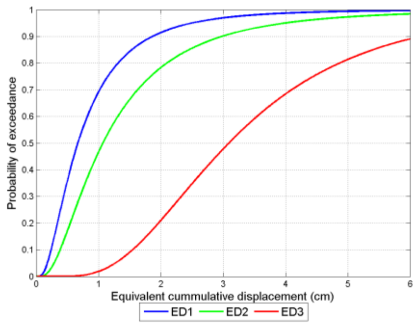
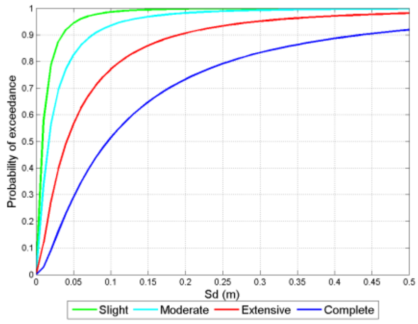
<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM:PGA</th></tr>
<tr><th>Damage state</th><th>Median</th><th>σ</th></tr>
<tr><td>LS1</td><td>0.63</td><td>0.55</td></tr>
<tr><td>LS2</td><td>1.24</td><td>0.55</td></tr>
<tr><td>LS3</td><td>–</td><td>0.55</td></tr>
<tr><td>LS4</td><td>–</td><td>0.55</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>LS1: Slight damage, LS2: Moderate damage
LS3: Extensive damage, LS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>PGA (g)</td></tr>
<tr><td>Uncertainties</td><td>Uncertainty on the demand is taken into account from the dispersion of the recorded damage indices as a function on the selected IM due to the variability of the seismic input motion. Damage state threshold uncertainty is accounted for by performing a Monte Carlo simulation. Uncertainty on the capacity properties of the building is considered depending on the code design level of the structure</td></tr>
<tr><td>Comments</td><td>Fragility curves based on three conditions; the geometry of the finite slopes, the soil properties of the slope material, the relative position of the building with respect to the slope crest</td></tr>
</table>

ID: LS-BL-FF-(Peduto *et al.* 2017)	
Hazard	Landslide
Asset	Building
Taxonomy	MUR+CLBRS
Typology of Structure	Single storey masonry structure
Country ISO	NPL
Approach	Empirical
References	Peduto, D., Ferlisi, S., Nicodemo, G., Reale, D., Pisciotta, G. & Gullà, G. (2017). Empirical Fragility and Vulnerability Curves for Buildings Exposed to Slow-Moving Landslides at Medium and Large Scales. Landslides 14(6): 1993–2007.
Figures	
Variables	**IM:PGA** **Damage state** **μ** ***σ*** ED1 0.22 0.37 ED2 0.39 0.37 ED3 0.58 0.37
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	ED1: Slight damage ED2: Moderate damage ED3: Complete damage
Intensity measure name	Equivalent cumulative displacement (cm)
Uncertainties	Uncertainty in the development of functions are related to peculiar factors that trigger the landslide, the spatial and temporal variability in the intensity parameter, the change in vulnerability value from one asset to another and the lack of comprehensive databases of damage
Comments	

	ID: LS-BL-FF-(Peduto et al., 2017)
Hazard	Landslide
Asset	Building
Taxonomy	MUR+CBS+MOC
Typology of Structure	Single storey masonry structure
Country ISO	NPL
Approach	Empirical
References	Peduto, D., Ferlisi, S., Nicodemo, G., Reale, D., Pisciotta, G. & Gullà, G. (2017). Empirical Fragility and Vulnerability Curves for Buildings Exposed to Slow-Moving Landslides at Medium and Large Scales. Landslides 14(6): 1993–2007.
Figures	
Variables	**IM:PGA** **Damage state** / **μ** / **σ** ED1 / 0.22 / 0.37 ED2 / 0.39 / 0.37 ED3 / 0.58 / 0.37
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	ED1: Slight damage ED2: Moderate damage ED3: Complete damage
Intensity measure name	Equivalent cumulative displacement (cm)
Uncertainties	Uncertainty in the development of functions are related to peculiar factors that trigger the landslide, the spatial and temporal variability in the intensity parameter, the change in vulnerability value from one asset to another and the lack of comprehensive databases of damage
Comments	

<table>
<tr><td colspan="2">ID: LS-BL-FF-(Haugen & Kaynia, 2010)</td></tr>
<tr><td>Hazard</td><td>Landslide</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+STRUB+MOM</td></tr>
<tr><td>Typology of Structure</td><td>Mud mortared masonry walls with stone or brick</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Haugen, E, & Kaynia, A. (2010). Vulnerability of Structures Impacted by Debris Flow. Landslides and Engineered Slopes. From the Past to the Future (June 2008): 381–87.</td></tr>
<tr><td>Figures</td><td>
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<tr><td colspan="3">IM:PGA</td></tr>
<tr><td>Damage state</td><td>μ</td><td>σ</td></tr>
<tr><td>Slight</td><td>0.0081</td><td>1.15</td></tr>
<tr><td>Moderate</td><td>0.0165</td><td>1.19</td></tr>
<tr><td>Extensive</td><td>0.0411</td><td>1.20</td></tr>
<tr><td>Complete</td><td>0.0960</td><td>1.18</td></tr>
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</td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>Slight damage
Moderate damage
Extensive damage
Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>Spectral displacement (cm)</td></tr>
<tr><td>Uncertainties</td><td></td></tr>
<tr><td>Comments</td><td></td></tr>
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<tr><td colspan="2">ID: LS-BL-FF-(Haugen & Kaynia, 2010)</td></tr>
<tr><td>Hazard</td><td>Landslide</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+CLBRS+MOM</td></tr>
<tr><td>Typology of Structure</td><td>Mud mortared masonry walls with stone or brick</td></tr>
<tr><td>Country ISO</td><td>NPL</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Haugen, E, & Kaynia, A. (2010). Vulnerability of Structures Impacted by Debris Flow. Landslides and Engineered Slopes. From the Past to the Future (June 2008): 381–87.</td></tr>
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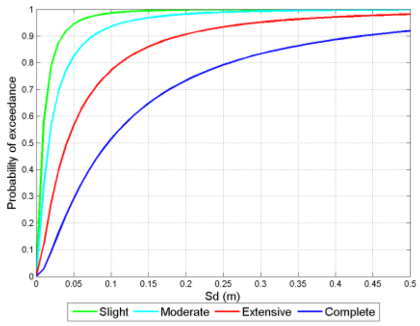

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<tr><th colspan="3">IM:PGA</th></tr>
<tr><th>Damage state</th><th>μ</th><th>σ</th></tr>
<tr><td>Slight</td><td>0.0081</td><td>1.15</td></tr>
<tr><td>Moderate</td><td>0.0165</td><td>1.19</td></tr>
<tr><td>Extensive</td><td>0.0411</td><td>1.20</td></tr>
<tr><td>Complete</td><td>0.0960</td><td>1.18</td></tr>
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<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>Slight damage
Moderate damage
Extensive damage
Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>Spectral displacement (cm)</td></tr>
<tr><td>Uncertainties</td><td></td></tr>
<tr><td>Comments</td><td></td></tr>
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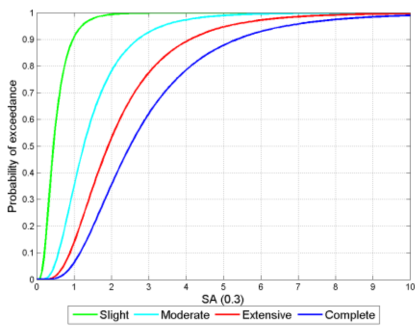
6. Fragility and Vulnerability Functions for Tanzania

6.1. Fragility functions for earthquake hazard

<table>
<tr><td colspan="2">ID: EQ-BL-FF-GEM-2019</td></tr>
<tr><td>Hazard</td><td>Earthquake</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>W/LN</td></tr>
<tr><td>Typology of Structure</td><td>Traditional housing typologies: Material technology; non-engineered wood members</td></tr>
<tr><td>Country ISO</td><td>TZA</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>GEM global vulnerability and fragility database</td></tr>
<tr><td>Figures</td><td>
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<tr><th colspan="3">IM: SA(0.3)</th></tr>
<tr><th>Damage States</th><th>μ</th><th>σ</th></tr>
<tr><td>Slight</td><td>0.4527</td><td>0.596</td></tr>
<tr><td>Moderate</td><td>1.2612</td><td>0.596</td></tr>
<tr><td>Extensive</td><td>1.9134</td><td>0.596</td></tr>
<tr><td>Complete</td><td>2.4974</td><td>0.596</td></tr>
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<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>DS1: Slight damage
DS2: Moderate damage
DS3: Extensive damage
DS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>Spectral acceleration (g)</td></tr>
<tr><td>Uncertainties</td><td>The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.</td></tr>
<tr><td>Comments</td><td></td></tr>
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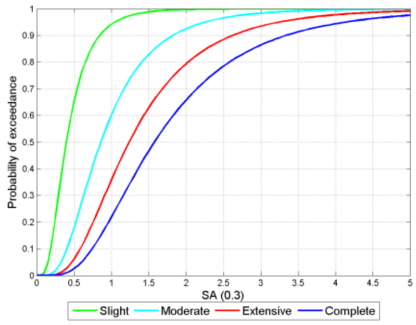
<table>
<tr><td colspan="2">ID: EQ-BL-FF-GEM-2019</td></tr>
<tr><td>Hazard</td><td>Earthquake</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>EU/LN</td></tr>
<tr><td>Typology of Structure</td><td>Traditional housing typologies. Material technology; Mud</td></tr>
<tr><td>Country ISO</td><td>TZA</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>GEM global vulnerability and fragility database</td></tr>
<tr><td>Figures</td><td>
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<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM: SA(0.3)</th></tr>
<tr><th>Damage States</th><th>μ</th><th>σ</th></tr>
<tr><td>Slight</td><td>0.399</td><td>0.586</td></tr>
<tr><td>Moderate</td><td>0.861</td><td>0.586</td></tr>
<tr><td>Extensive</td><td>1.238</td><td>0.586</td></tr>
<tr><td>Complete</td><td>1.577</td><td>0.586</td></tr>
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<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>DS1: Slight damage
DS2: Moderate damage
DS3: Extensive damage
DS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>Spectral acceleration (g)</td></tr>
<tr><td>Uncertainties</td><td>The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.</td></tr>
<tr><td>Comments</td><td></td></tr>
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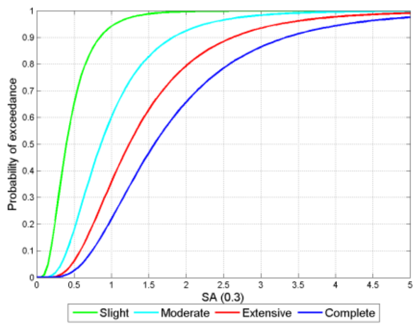
<table>
<tr><td colspan="2">ID: EQ-BL-FF-GEM-2019</td></tr>
<tr><td>Hazard</td><td>Earthquake</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+ADO+MOM</td></tr>
<tr><td>Typology of Structure</td><td>Unreinforced masonry bearing wall structure. Material technology; Adobe with mud mortar</td></tr>
<tr><td>Country ISO</td><td>TZA</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>GEM global vulnerability and fragility database</td></tr>
<tr><td>Figures</td><td>
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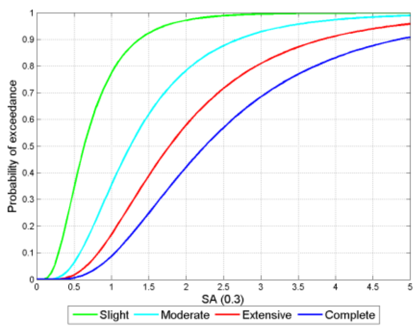
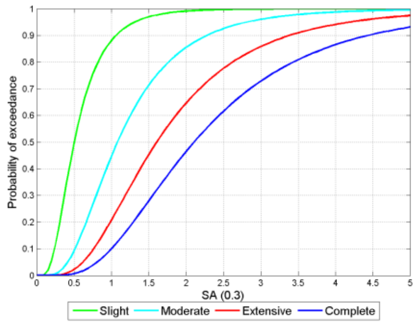
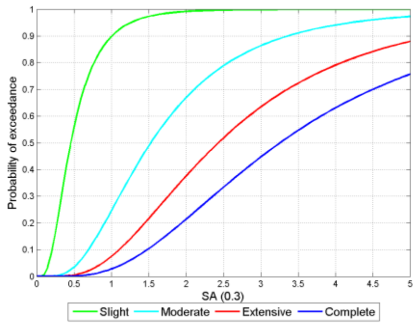
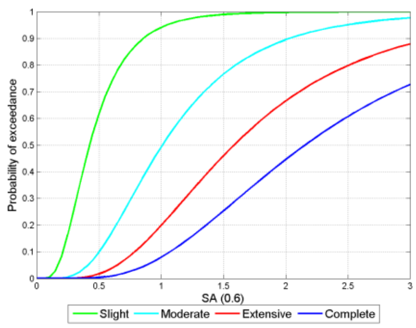
<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM: SA(0.3)</th></tr>
<tr><th>Damage States</th><th>μ</th><th>σ</th></tr>
<tr><td>Slight</td><td>0.399</td><td>0.586</td></tr>
<tr><td>Moderate</td><td>0.861</td><td>0.586</td></tr>
<tr><td>Extensive</td><td>1.238</td><td>0.586</td></tr>
<tr><td>Complete</td><td>1.577</td><td>0.586</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>DS1: Slight damage
DS2: Moderate damage
DS3: Extensive damage
DS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>Spectral acceleration (g)</td></tr>
<tr><td>Uncertainties</td><td>The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.</td></tr>
<tr><td>Comments</td><td></td></tr>
</table>

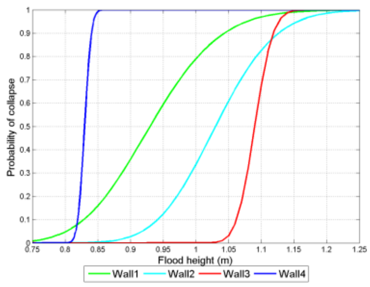
<table>
<tr><td colspan="2">ID: EQ-BL-FF-GEM-2019</td></tr>
<tr><td>Hazard</td><td>Earthquake</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+CLBRS+MOM</td></tr>
<tr><td>Typology of Structure</td><td>Unreinforced masonry bearing wall structures. Material technology; Fired clay bricks with mud mortar</td></tr>
<tr><td>Country ISO</td><td>TZA</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>GEM global vulnerability and fragility database</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td><table>
<tr><th colspan="3">IM: SA(0.3)</th></tr>
<tr><th>Damage States</th><th>μ</th><th>σ</th></tr>
<tr><td>Slight</td><td>0.399</td><td>0.586</td></tr>
<tr><td>Moderate</td><td>0.861</td><td>0.586</td></tr>
<tr><td>Extensive</td><td>1.238</td><td>0.586</td></tr>
<tr><td>Complete</td><td>1.577</td><td>0.586</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>DS1: Slight damage
DS2: Moderate damage
DS3: Extensive damage
DS4: Complete damage</td></tr>
<tr><td>Intensity measure name</td><td>Spectral acceleration (g)</td></tr>
<tr><td>Uncertainties</td><td>The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.</td></tr>
<tr><td>Comments</td><td></td></tr>
</table>

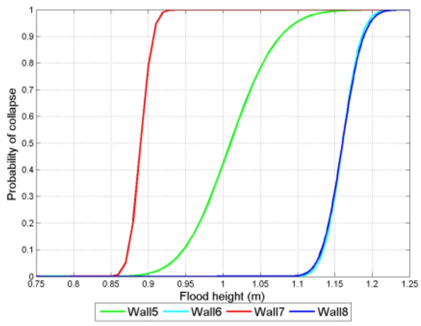
ID: EQ-BL-FF-GEM-2019	
Hazard	Earthquake
Asset	Building
Taxonomy	MUR+CBS+MOC
Typology of Structure	Unreinforced masonry bearing wall structures. Material technology; Concrete blocks with cement mortar.
Country ISO	TZA
Approach	Analytical
References	GEM global vulnerability and fragility database
Figures	
Variables	**IM: SA(0.3)** **Damage States** / **μ** / **σ** Slight 0.5043 0.581 Moderate 1.0820 0.581 Extensive 1.6088 0.581 Complete 2.1073 0.581
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Spectral acceleration (g)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.
Comments	

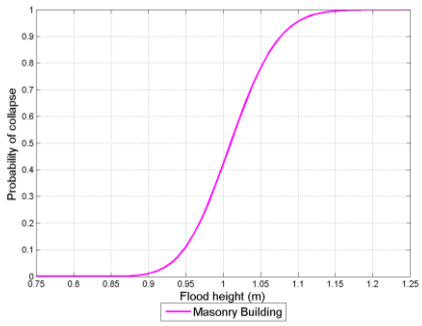
ID: EQ-BL-FF-GEM-2019	
Hazard	Earthquake
Asset	Building
Taxonomy	CR/LFINF
Typology of Structure	Infilled frames concrete reinforced structure
Country ISO	TZA
Approach	Analytical
References	GEM global vulnerability and fragility database
Figures	
Variables	**IM: SA(0.3)** **Damage States** — **μ** — **σ** Slight 0.4579 0.615 Moderate 1.5283 0.615 Extensive 2.4308 0.615 Complete 3.2585 0.615
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Spectral acceleration (g)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.
Comments	

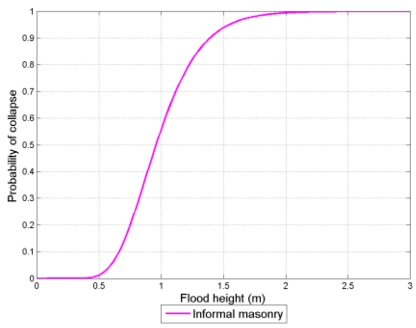
ID: EQ-BL-FF-GEM-2019	
Hazard	Earthquake
Asset	Building
Taxonomy	CR/LFM
Typology of Structure	Moment frame concrete reinforced structure
Country ISO	TZA
Approach	Analytical
References	GEM global vulnerability and fragility database
Figures	
Variables	**IM: SA(0.3)** **Damage States** / **μ** / **σ** Slight / 0.4579 / 0.545 Moderate / 1.5283 / 0.545 Extensive / 2.4308 / 0.545 Complete / 3.2585 / 0.545
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	DS1: Slight damage DS2: Moderate damage DS3: Extensive damage DS4: Complete damage
Intensity measure name	Spectral acceleration (g)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.
Comments	

6.2. Fragility functions for floods

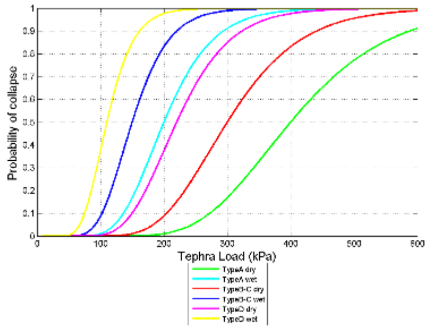
	ID: FL-BL-FF-(Jalayer, *et al.,* 2016)
Hazard	Flood
Asset	Building
Taxonomy	MUR+CLBRS, MUR+CBS, MCF
Typology of Structure	Non engineered regular masonry with cement blocks/bricks
Country ISO	TZA
Approach	Analytical
References	Jalayer, F., Carozza, S., De Risi, R., Manfredi, G. & Mbuya, E. (2016). Performance-Based Flood Safety-Checking for Non-Engineered Masonry Structures. Engineering Structures 106: 109–23. http://dx.doi.org/10.1016/j.engstruct.2015.10.007.
Figures	
Variables	**IM: Flood height (m)** **Cases** **Median** **CoV** Wall 1 0.93 0.09 Wall 2 1.03 0.03 Wall 3 1.09 0.02 Wall 4 0.83 0.01
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	***Collapse damage state conditioned on different sides of the walls of varying factored critical flooding height*** Wall 1, Wall 2, Wall 3, Wall 4
Intensity measure name	Flood height (m)
Uncertainties	The structural fragility was calculated taking into account the uncertainties in loading and material properties and by using an efficient Bayesian procedure providing a robust fragility curve and its plus minus one standard deviation confidence interval (Jalayer, *et al.,* 2016).

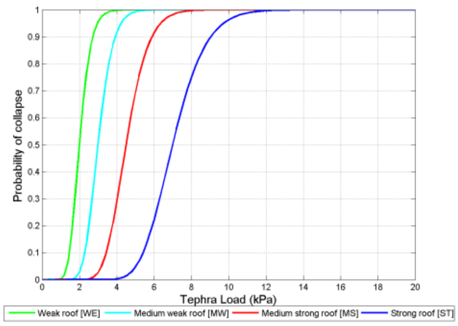
<table>
<tr><td colspan="2">ID: FL-BL-FF-(Jalayer et al., 2016)</td></tr>
<tr><td>Hazard</td><td>Flood</td></tr>
<tr><td>Asset</td><td>Building</td></tr>
<tr><td>Taxonomy</td><td>MUR+CLBRS, MUR+CBS, MCF</td></tr>
<tr><td>Typology of Structure</td><td>Non engineered regular masonry with cement blocks</td></tr>
<tr><td>Country ISO</td><td>TZA</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Jalayer, F., Carozza, S., De Risi, R., Manfredi, G. & Mbuya, E. (2016). Performance-Based Flood Safety-Checking for Non-Engineered Masonry Structures. Engineering Structures 106: 109–23. http://dx.doi.org/10.1016/j.engstruct.2015.10.007.</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td>
<table>
<tr><th colspan="3">IM: Flood height (m)</th></tr>
<tr><th>Cases</th><th>Median</th><th>σ</th></tr>
<tr><td>Wall 5</td><td>1.01</td><td>0.05</td></tr>
<tr><td>Wall 6</td><td>1.16</td><td>0.017</td></tr>
<tr><td>Wall 7</td><td>0.89</td><td>0.014</td></tr>
<tr><td>Wall 8</td><td>1.16</td><td>0.019</td></tr>
</table>
</td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>Collapse damage state conditioned on different sides of the walls of varying factored critical flooding height
Wall 5, Wall 6, Wall 7</td></tr>
<tr><td>Intensity measure name</td><td>Flood height (m)</td></tr>
<tr><td>Uncertainties</td><td>The structural fragility was calculated taking into account the uncertainties in loading and material properties and by using an efficient Bayesian procedure providing a robust fragility curve and its plus minus one standard deviation confidence interval.</td></tr>
</table>

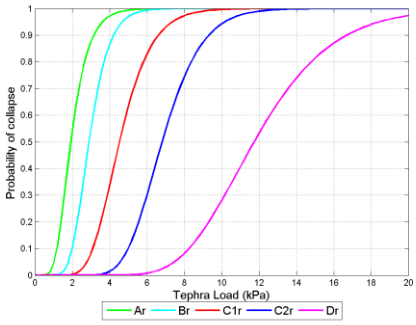
	ID: FL-BL-FF-(Jalayer et al., 2016)
Hazard	Flood
Asset	Building
Taxonomy	MUR+CLBRS, MUR+CBS, MCF
Typology of Structure	Non engineered regular masonry with cement blocks
Country ISO	TZA
Approach	Analytical
References	Jalayer, F., Carozza, S., De Risi, R., Manfredi, G. & Mbuya, E. (2016). Performance-Based Flood Safety-Checking for Non-Engineered Masonry Structures. Engineering Structures 106: 109–23. http://dx.doi.org/10.1016/j.engstruct.2015.10.007.
Figures	
Variables	**IM: Flood height (m)** **Case** / **Median** / **σ** Entire building / 0.83 / 0.015
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	***Collapse damage state conditioned on entire performance of the building*** Building
Intensity measure name	Flood height (m)
Uncertainties	The structural fragility was calculated taking into account the uncertainties in loading and material properties and by using an efficient Bayesian procedure providing a robust fragility curve and its plus minus one standard deviation confidence interval.
Comments	

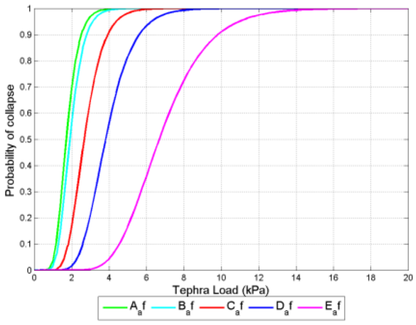
ID: FL-BL-FF-(Risi *et al.,* 2013)	
Hazard	Flood
Asset	Building
Taxonomy	MUR+ADO, EU+ETR, MUR+CLRBS, MUR+CBS
Typology of Structure	Informal construction (Adobe, rammed earth or cement stabilised blocks) with corrugated iron sheets
Country ISO	TZA
Approach	Analytical
References	Risi, R., Jalayer, F., Paola, F., Iervolino, I., Giugni, M., Topa, E., Mbuya, E., Kyessi, A., Manfredi, G. & Gasparini, P. (2013). Flood Risk Assessment for Informal Settlements. Natural Hazards 69(1): 1003–32. http://link.springer.com/10.1007/s11069-013-0749-0.
Figures	
Variables	**IM: Flood height (m)** **Case** / **Median** / **σ** Building / 0.9598 / 0.29
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	***Collapse damage state***
Intensity measure name	Flood height (m)
Uncertainties	The uncertainties taken into account in the assessment of structural vulnerability can be classified into those related to material mechanical properties and those related to structural detailing and geometry
Comments	

6.3. Fragility functions for volcanic ashfall

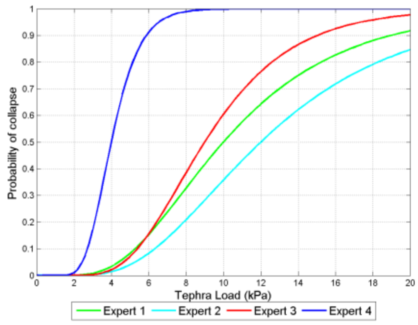
<table>
<tr><td colspan="2">ID: VL-BL-FF-(Pomonis, et al., 1999)</td></tr>
<tr><td>Hazard</td><td>Volcanoes</td></tr>
<tr><td>Asset</td><td>Buildings</td></tr>
<tr><td>Taxonomy</td><td>MUR+STRUB, MUR+STRDE
MUR+CBS, CR+LFINF</td></tr>
<tr><td>Typology of Structure</td><td>Rubble stone, load-bearing masonry; Dressed stone load-bearing masonry; Concrete block masonry; Reinforced concrete frame</td></tr>
<tr><td>Country ISO</td><td>TZA</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Pomonis, A., Spence, R. & Baxter, P. (1999). Risk Assessment of Residential Buildings for an Eruption of Furnas Volcano, Sao Miguel, the Azores. Journal of Volcanology and Geothermal Research 92(1–2): 107–31.</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td>IM : Tephra thickness (mm)
<table>
<tr><th>Damage Stage</th><th>Median</th><th>σ</th></tr>
<tr><td>TypeA_dry</td><td>400</td><td>0.3</td></tr>
<tr><td>TypeA_wet</td><td>200</td><td>0.3</td></tr>
<tr><td>TypeB,C_dry</td><td>300</td><td>0.3</td></tr>
<tr><td>TypeB,C_wet</td><td>150</td><td>0.3</td></tr>
<tr><td>TypeD_dry</td><td>220</td><td>0.3</td></tr>
<tr><td>TypeD_wet</td><td>110</td><td>0.3</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>Collapse damage conditioned on different roof types;
Type A roof - dry tephra; Type A roof - wet tephra; Type B,C roof - dry tephra; Type B,C roof - wet tephra; Type D roof - dry tephra; Type D roof - wet tephra</td></tr>
<tr><td>Intensity measure name</td><td>Tephra thickness (mm)</td></tr>
<tr><td>Uncertainties</td><td></td></tr>
<tr><td>Comments</td><td></td></tr>
</table>

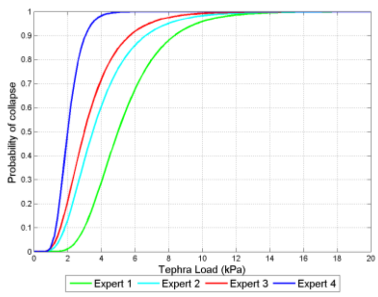
	ID: VL-BL-FF-(Spence *et al.,* 2005)
Hazard	Volcanoes
Asset	Buildings
Taxonomy	MUR+STRUB, MUR+STRDE MUR+CBS, CR+LFINF
Typology of Structure	Vaulted and reinforced concrete roofs, Tile roofs, Metal sheet roof and Slab roof terrace
Country ISO	TZA
Approach	Hybrid
References	Spence, R., Kelman, I., Baxter, P., Zuccaro, G. & Petrazzuoli, S. (2005). Residential Building and Occupant Vulnerability to Tephra Fall. Natural Hazards and Earth System Sciences 5: 477–94.
Figures	
Variables	**IM: Tephra Load (KPa)** **Damage States** / **Median** / **σ** WE 2.0 0.24 MW 3.0 0.21 MS 4.5 0.21 ST 7.0 0.20
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	***Collapse damage conditioned on different roof types*** Weak roof [WE] Medium weak roof [MW] Medium strong roof [MS] Strong roof [ST]
Intensity measure name	Tephra load (KPa)
Uncertainties	
Comments	

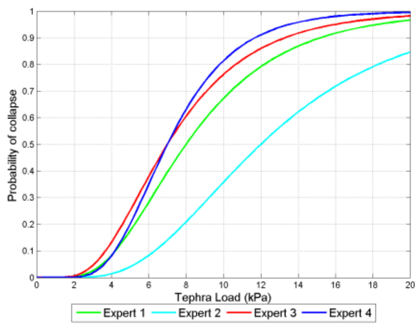
<table>
<tr><td colspan="2">ID: VL-BL-FF-(Zuccaro et al., 2008)</td></tr>
<tr><td>Hazard</td><td>Volcanoes</td></tr>
<tr><td>Asset</td><td>Buildings</td></tr>
<tr><td>Taxonomy</td><td>MUR+STRUB, MUR+STRDE
MUR+CBS, CR+LFINF</td></tr>
<tr><td>Typology of Structure</td><td>Weak masonry rubble stone structures; Medium quality masonry rubble stone structure; Good masonry structures; Framed buildings (RC and Steel)</td></tr>
<tr><td>Country ISO</td><td>ITA</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Zuccaro, G., Cacace, F., Spence, R.J.S. & Baxter, P.J. (2008). Impact of Explosive Eruption Scenarios at Vesuvius. Journal of Volcanology and Geothermal Research 178(3): 416–53. http://dx.doi.org/10.1016/j.jvolgeores.2008.01.005.</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td><table>
<tr><td colspan="3">IM: Tephra Load (KPa)</td></tr>
<tr><td>Damage States</td><td>Median</td><td>σ</td></tr>
<tr><td>Ar</td><td>1.931</td><td>0.383</td></tr>
<tr><td>Br</td><td>2.899</td><td>0.292</td></tr>
<tr><td>C1r</td><td>4.533</td><td>0.295</td></tr>
<tr><td>C2r</td><td>6.821</td><td>0.243</td></tr>
<tr><td>Dr</td><td>11.74</td><td>0.275</td></tr>
</table></td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>Collapse damage conditioned on different roof types;
Weak pitched wooden roof [Ar]; Flat standard wooden roof, Reinforced concrete flat roof [Br]; Flat RC roof older than 20years [C1r]; Flat RC roof younger than 20 years [C2r]; Recent flat RC roof, recent pitched RC roof, recent steel pitched roof [Dr]</td></tr>
<tr><td>Intensity measure name</td><td>Tephra load (KPa)</td></tr>
<tr><td>Uncertainties</td><td>Considerable uncertainty in the evaluation of the cumulative damage on the building typologies and in the graduation of the damage levels attributed by the combined fragility functions for each event.</td></tr>
<tr><td>Comments</td><td></td></tr>
</table>

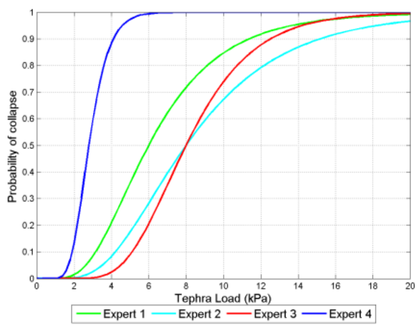
<table>
<tr><td colspan="2">ID: VL-BL-FF-(Jenkins et al., 2014)</td></tr>
<tr><td>Hazard</td><td>Volcanoes</td></tr>
<tr><td>Asset</td><td>Buildings</td></tr>
<tr><td>Taxonomy</td><td>W+WLI, RC+LINF, URM, MCF</td></tr>
<tr><td>Typology of Structure</td><td>Timber frame with bamboo weave or timber infill and palm frond roofs
Timber frame with bamboo weave or timber infill and corrugated steel roof
Reinforced concrete frame buildings with corrugated steel roofs
Mixed construction buildings with corrugated steel roofs
Rubble stone masonry building with concrete roof
Confined masonry building with a reinforced concrete roof
Cut block masonry building with reinforced concrete roof</td></tr>
<tr><td>Country ISO</td><td>ITA</td></tr>
<tr><td>Approach</td><td>Analytical</td></tr>
<tr><td>References</td><td>Jenkins, S.F., Spence, R.J.S., Fonseca, J.F.B.D., Solidum, R.U. & Wilson, T.M. (2014). Volcanic Risk Assessment: Quantifying Physical Vulnerability in the Built Environment. Journal of Volcanology and Geothermal Research 276: 105–20. http://dx.doi.org/10.1016/j.jvolgeores.2014.03.002.</td></tr>
<tr><td>Figures</td><td>
</td></tr>
<tr><td>Variables</td><td>
<table>
<tr><th colspan="3">IM: Tephra Load (KPa)</th></tr>
<tr><th>Damage States</th><th>Median</th><th>σ</th></tr>
<tr><td>A_af</td><td>1.721</td><td>0.3</td></tr>
<tr><td>B_af</td><td>1.912</td><td>0.3</td></tr>
<tr><td>C_af</td><td>2.677</td><td>0.3</td></tr>
<tr><td>D_af</td><td>3.824</td><td>0.3</td></tr>
<tr><td>E_af</td><td>6.692</td><td>0.3</td></tr>
</table>
</td></tr>
<tr><td>Vulnerability function mathematical model</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>Damage state names</td><td>Collapse damage conditioned on different roof types;
Weak timber boards on timber rafters/trusses, metal sheet roofs on timber rafters/trusses in poor condition [A_af]
Long span roofs with metal sheet or fiber reinforced concrete sheets [B_af]
Metal sheet roofs on timber rafters/trusses in average condition, tiles on timber rafters/trusses in average condition [C_af]
Metal sheet roofs on timber rafters/trusses in good condition, strong timber on timber rafters/trusses in average or good condition [D_af]
Flat RC roof designed for access and in general good condition [E_af]</td></tr>
</table>

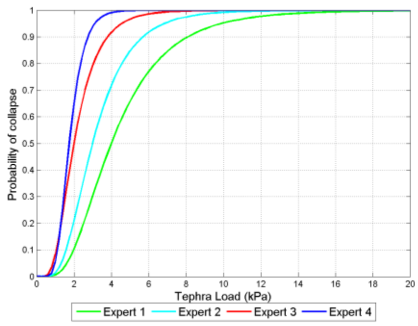
Intensity measure name	Tephra load (KPa)
Uncertainties	Uncertainties associated with each estimate are propagated through any risk modelling or forecasting, ideally using probabilistic techniques, which ensure that the full spectrum of possible outcomes is considered.
Comments	

<table>
<tr><td colspan="2">ID: VL-BL-FF-(Blong, *et al.*, 2017)</td></tr>
<tr><td>**Hazard**</td><td>Volcanoes</td></tr>
<tr><td>**Asset**</td><td>Buildings</td></tr>
<tr><td>**Taxonomy**</td><td>W1-NonEng-H</td></tr>
<tr><td>**Typology of Structure**</td><td>Light frame wood, non-engineered, roof pitch=>35°</td></tr>
<tr><td>**Country ISO**</td><td>TZA</td></tr>
<tr><td>**Approach**</td><td>Analytical</td></tr>
<tr><td>**References**</td><td>Blong, R.J., Grasso, P., Jenkins, S.F., Magill, C.R., Wilson, T.M., McMullan, K. & Kandlbauer, J. (2017). Estimating Building Vulnerability to Volcanic Ash Fall for Insurance and Other Purposes. Journal of Applied Volcanology. http://dx.doi.org/10.1186/s13617-017-0054-9.</td></tr>
<tr><td>**Figures**</td><td>
</td></tr>
<tr><td>**Variables**</td><td><table><tr><th colspan="3">IM: Tephra Load (KPa)</th></tr><tr><th>Damage States</th><th>Median</th><th>σ</th></tr><tr><td>Expert 1</td><td>10</td><td>0.5</td></tr><tr><td>Expert 2</td><td>12</td><td>0.5</td></tr><tr><td>Expert 3</td><td>9</td><td>0.4</td></tr><tr><td>Expert 4</td><td>4</td><td>0.3</td></tr></table></td></tr>
<tr><td>**Vulnerability function mathematical model**</td><td>Lognormal cumulative distribution</td></tr>
<tr><td>**Damage state names**</td><td>***Collapse damage state conditioned on work of four experts;***
Expert 1, Expert 2, Expert 3 and Expert 4</td></tr>
<tr><td>**Intensity measure name**</td><td>Tephra load (KPa)</td></tr>
<tr><td>**Uncertainties**</td><td>The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.</td></tr>
</table>

ID: VL-BL-FF-(Blong *et al.*, 2017)	
Hazard	Volcanoes
Asset	Buildings
Taxonomy	W2/S3-NonEng-M
Typology of Structure	Commercial and industrial, non-engineered, roof pitch =6-35°
Country ISO	TZA
Approach	Analytical
References	Blong, R.J., Grasso, P., Jenkins, S.F., Magill, C.R., Wilson, T.M., McMullan, K. & Kandlbauer, J. (2017). Estimating Building Vulnerability to Volcanic Ash Fall for Insurance and Other Purposes. Journal of Applied Volcanology. http://dx.doi.org/10.1186/s13617-017-0054-9.
Figures	**IM: Tephra Load (KPa)** **Damage States** / **Median** / **σ** Expert 1 / 5.0 / 0.4 Expert 2 / 3.5 / 0.5 Expert 3 / 3.0 / 0.5 Expert 4 / 2.0 / 0.3
Variables	
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	***Collapse damage state conditioned on work of four experts;*** Expert 1, Expert 2, Expert 3 and Expert 4
Intensity measure name	Tephra load (KPa)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.

ID: VL-BL-FF-(Blong *et al.,* 2017)	
Hazard	Volcanoes
Asset	Buildings
Taxonomy	C3M/RMM-Eng-M
Typology of Structure	Concrete fame / reinforced masonry, engineered, roof pitch<6°
Country ISO	TZA
Approach	Analytical
References	Blong, R.J., Grasso, P., Jenkins, S.F., Magill, C.R., Wilson, T.M., McMullan, K. & Kandlbauer, J. (2017). Estimating Building Vulnerability to Volcanic Ash Fall for Insurance and Other Purposes. Journal of Applied Volcanology. http://dx.doi.org/10.1186/s13617-017-0054-9.
Figures	
Variables	**IM: Tephra Load (KPa)** **Damage States** / **Median** / **σ** Expert 1 / 8 / 0.5 Expert 2 / 12 / 0.5 Expert 3 / 7 / 0.5 Expert 4 / 7 / 0.3
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	***Collapse damage state conditioned on work of four experts;*** Expert 1, Expert 2, Expert 3 and Expert 4
Intensity measure name	Tephra load (KPa)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.

ID: VL-BL-FF-(Blong *et al.,* 2017)	
Hazard	Volcanoes
Asset	Buildings
Taxonomy	URML-M
Typology of Structure	Non -engineered/unreinforced masonry bearing walls, roof pitch=6-35°
Country ISO	TZA
Approach	Analytical
References	Blong, R.J., Grasso, P., Jenkins, S.F., Magill, C.R., Wilson, T.M., McMullan, K. & Kandlbauer, J. (2017). Estimating Building Vulnerability to Volcanic Ash Fall for Insurance and Other Purposes. Journal of Applied Volcanology. http://dx.doi.org/10.1186/s13617-017-0054-9.
Figures	
Variables	**IM: Tephra Load (KPa)** **Damage States** / **Median** / **σ** Expert 1 / 6.0 / 0.50 Expert 2 / 8.0 / 0.50 Expert 3 / 8.0 / 0.36 Expert 4 / 2.8 / 0.30
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	***Collapse damage state conditioned on work of four experts;*** Expert 1, Expert 2, Expert 3 and Expert 4
Intensity measure name	Tephra load (KPa)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.

ID: VL-BL-FF-(Blong *et al.,* 2017)	
Hazard	Volcanoes
Asset	Buildings
Taxonomy	PBC-L
Typology of Structure	Informal post and beam construction, roof pitch <6°
Country ISO	TZA
Approach	Analytical
References	Blong, R.J., Grasso, P., Jenkins, S.F., Magill, C.R., Wilson, T.M., McMullan, K. & Kandlbauer, J. (2017). Estimating Building Vulnerability to Volcanic Ash Fall for Insurance and Other Purposes. Journal of Applied Volcanology. http://dx.doi.org/10.1186/s13617-017-0054-9.
Figures	
Variables	**IM: Tephra Load (KPa)** **Damage States** / **Median** / **σ** Expert 1 / 4.0 / 0.5 Expert 2 / 3.0 / 0.5 Expert 3 / 2.0 / 0.5 Expert 4 / 1.8 / 0.3
Vulnerability function mathematical model	Lognormal cumulative distribution
Damage state names	***Collapse damage state conditioned on work of four experts;*** Expert 1, Expert 2, Expert 3, Expert 4
Intensity measure name	Tephra load (KPa)
Uncertainties	The uncertainties associated with the capacity, the displacement-based damage model, the inventory of existing buildings and the seismic demand are taken into consideration.
Comments	

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