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Building typology classification and earthquake vulnerability scale of Central and South Asian building stock

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ABSTRACT

The typology classification of any building is essential to understand its structural and architectural configuration, to empirically evaluate its vulnerability, or to provide the basis for creating a structural model and to analytically study its dynamic performance. A typology classification may help structural engineers, architects and urban planners to understand a building's behavior and response to any type of natural or man-made hazard as well as further assists in defining improvement techniques and long-term sustainable regional planning. The division of a building stock into distinct classes of building typologies and hence the definition of a thorough building classification scheme is a major prerequisite for any vulnerability or loss assessment study.

A building's typology largely depends upon the local geology and geography, climatic conditions, socio-economic status of the occupants or owners, and to a large extent the locally available construction skills as well as natural resources (with respect to construction materials). The type of natural hazards a region has experienced in the past may also influence its prevalent construction typologies, at least if these hazards frequently occur in a certain period of time. The introduction of new construction technologies, design codes and/or building byelaws have further implications on the question of which building typologies are prevalent in a certain region, given that these legal provisions are implemented in daily construction practice. Focusing on Central and South Asian conditions, large variations exist in above stated factors. The region the Disaster Risk Management Initiative programme (DRMI), led by the Aga Khan Development Network (AKDN), is focused on here comprises of the Central Asian countries Tajikistan and Kyrgyzstan as well as the South Asian countries Afghanistan, India and Pakistan. As strong variations in the characteristics of a certain building typology may exist between different regions or even countries, the definition of building typology classes at a regional scale is a daunting task. The present article attempts to categorize the Central and South Asian building stock into a manageable number of regional building typologies based on extensive field studies in the different regions. It further includes a thorough review of the relevant building classification schemes, discusses empirical data collection, and defines the criteria for building classification. By reviewing the buildings' dynamic performances, a final building classification for the region and a customized visual screening-based vulnerability scale is presented.

1. Introduction

The categorization of buildings into distinct typology classes has become a major task for any earthquake loss estimation (ELE) study and should be preferably conducted at the study's very beginning. Defining a distinct number of building typology classes according to their expected vulnerability, i.e., damageability, during earthquake shaking definitely facilitates an easier conduct of ELE studies. The demand for building classification schemes in ELE stems from the fact that it is virtually impossible to consider each building with its individual structural and non-structural peculiarities for an area or region with hundreds, often thousands of individual buildings. Grouping buildings into a certain number of typology classes thus represents a compromise to allow a more manageable and efficient study while still maintaining the integrity of the study's results [18]. Another reason for this sort of categorization is to define a common terminology or taxonomy in order to document variations in building design and construction practices around the world [3].

Building classification schemes have evolved from macroseismic intensity scales, such as the MSK–64 scale (short for

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Table 1
Comparison of assigned Vulnerability Classes following EMS–98 and MSK–64.

Material	*Type of structure*	*Vulnerability Class acc. to* EMS–98[a]			MSK–64
Masonry	Rubble stone, fieldstone		**A**		A
	Adobe (earth brick)		**A**	(—B)	A
	Simple stone	(A—)	**B**		A
	Massive stone	(B—)	**C**	(—D)	B
	Unreinforced, with manufactured stone units	(A—)	**B**	(—C)	B
	Unreinforced, with RC floors	(B—)	**C**	(—D)	B
	Reinforced or confined	(C—)	**D**	(—E)	(C)[b]
Reinforced concrete (RC)	Frame without ERD	(A—)(B—)	**C**	(—D)	C
	Frame with moderate level of ERD	(B—)(C—)	**D**	(—E)	
	Frame with high level of ERD	(C—)(D—)	**E**	(—F)	
	Walls without ERD	(B—)	**C**	(—D)	
	Walls with moderate level of ERD	(C—)	**D**	(—E)	
	Walls with high level of ERD	(D—)	**E**	(—F)	
Steel	Steel structures	(C—)(D—)	**E**	(—F)	
Wood	Timber structures	(B—)(C—)	**D**	(—E)	B – C[c]

[a] **A** – most likely, (—) less probable range, (—) probable range of Vulnerability Class.

[b] Building typology was not yet defined.

[c] If well-built, Vulnerability Class C shall be assigned.

Medvedev–Sponheuer–Karnik scale [31,22]). In the MSK–64 scale, buildings were initially classified according to their material as well as type of load-bearing system into three distinct, so-called, *Vulnerability Classes* A, B and C. The classification scheme of MSK–64 was later adopted by the European Macroseismic Scale EMS [11,12] and complemented by three more classes D, E and F in order to account for more work materials (e.g. structural steel) as well as various (improved) levels of earthquake-resistant design (ERD). The different Vulnerability Classes assigned to the various structural types following EMS–98 and MSK–64 are compared in Table 1.

The concept of vulnerability classes is intimately connected to the empirical approach of ELE where seismic ground motion is mainly expressed in terms of macroseismic intensity. Irrespective of the various shortcomings that come along with the empirical approach [18], the concept of vulnerability classes represents a significant simplification for building typology classification. Vulnerability classes are assigned based on work materials and structural systems (and partly the level of earthquake-resistant design) while often completely neglecting the buildings' height range (expressed in terms of story number). Since this classification concept further allows for the assignment of buildings of completely different materials to the same vulnerability, it should definitely be handled with care.

Later on, with the first release of FEMA's and NIBS's HAZUS methodology in 1997 (HAZUS® 97 [7],[1]), a new concept of building classification was also introduced. The HAZUS methodology suggested categorizing the existing building stock into a certain number of prevalent, so-called *Model Building Typologies* (MBT) considering structural type, height range as well as level of code design as the main classification criteria. This procedure leads to more typology classes than the six vulnerability classes of the empirical approach, and is able to address the different features of buildings in a more precise way. Many ELE projects and initiatives that came up in the following years have taken up this concept for building stock classification, as e.g. WHE–PAGER (www.world-housing.net), Risk–UE [24], the parameterless scale of intensity PSI [30].

More recently, another approach of building classification has been described by the GEM Building Taxonomy (www.globalquakemodel.org [3]), which describes a building by attributes that affect its seismic performance. The attributes are specific building characteristics such as the work material, lateral load-resisting system, height (number of stories), etc. The current version of GEM'S Building Taxonomy defines 13 attributes in total, with a high level of detail compared to other building classification schemes. However, the high level of detail and precision makes this approach more of a description of an individual building rather than characterizing a certain building typology class. The actual building classification has to come in a second step after it is decided which attributes are classified into the same or separate typology classes. Another disadvantage of this approach consists in the fact that, given that all attributes are assigned, the GEM taxonomy leads to very long barcode-like acronyms for each building (class) considered, making it very difficult to handle it on a larger scale or by more unexperienced users.

2. Development of building typology and vulnerability classification scheme

The main purpose of any building classification is to group buildings or building typologies that show comparable overall performance during earthquake shaking, i.e., that have similar vulnerability (dameageability).

2.1. Structural system and geometric configuration-based criteria

Any building typology class shall include those typologies that are similar with respect to structural system, work materials applied, size (both in terms of height range and footprint area) as well as socio-economic parameters (i.e. building replacement value, number of occupants etc). Needless to say that the main parameter influencing structural vulnerability is the building's structural system, which is a combination of the construction materials used and the primary load-bearing structure. Secondary classification parameters may be overall building height, level of code design and/or period of construction. A condensed overview of the major international building classification schemes as well as their respective classification criteria is provided in Table 2.

Though the majority of classification schemes attempt to address all possible construction typologies, many locally available vernacular typologies are not included at all or are only represented by a coarse variation of the same. On the other hand, the majority of typologies included in the global schemes will not be available in a certain region

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[1] Since its first release in 1997 a number of releases and updates of this methodology have been published (e.g. HAZUS®99 [8], HAZUS®MH [10]).

Table 2
Overview of major building classification schemes considering structural system and geometric configuration.

Name (Reference)	Regional applicability	No. of typology classes	Classification criteria			
			(Wall) construction material	Load-bearing structure	Height Range	Level of code design
ATC-13 [1]	U.S.	40 typologies over 17 building classes	✓	✓	✓	–
PSI [30]	Global	worldwide typologies	✓	✓	–	–
RISK–UE [21,24]	Europe	65 typologies over 23 building classes	✓	✓	✓	–
WHE[a] (www.world-housing.net)	Global	45 subtypes over 14 load-bearing typologies	✓	✓	–	–
HAZUS–MH [10]	U.S.	36 model building types over 15 building classes	✓	✓	✓	✓
UN–Habitat [33]	Global	20 wall type classes	✓	–	–	–
PAGER[b] [15]	Global	81 typologies over 9 material classes	✓	✓	✓	–
GEM[c] [3]	Global	13 attributes are defined, associated with specific building characteristics	✓	✓	✓	✓
SYNER-G Taxonomy [13]	Europe	32 main categories and 44 sub-categories	✓	✓	✓	✓
EMCA Building Typology [36]	Central Asia[d]	16 subtypes over 6 material/load-bearing classes	✓	✓	(✓)	(✓)

[a] The purpose of this classification scheme provided by the World Housing Encyclopedia (WHE) is to allow contributors/users an easier categorization of housing typologies.
[b] See also http://pager.world-housing.net.
[c] Global Earthquake Model taxonomy.
[d] Tajikistan, Kazakhstan, Turkmenistan, Uzbekistan, Kyrgyzstan.

or test bed. It should therefore be contemplated to develop customized classification schemes for any test bed of ELE studies. These schemes may be combinations of extracts from various global classification schemes complemented by locally available building typologies that are not addressed by any global classification scheme.

2.2. Geographical distribution and socio-economic conditions criteria

In addition to structural system and geometric configuration-related factors, the prevalence of a certain construction typology depends on a variety of factors related to geographical distribution and socio-economic conditions, i.e.:

- local availability of building construction materials, which is again dependent on:
  - ○ Geological and topographical conditions: Both the subsurface geology and the surface topography of the region have strong impact on the availability of construction materials such as mud, sand, gravels, boulders, slate stones, dressed stones, etc. The presence of rivers or lakes, or if the considered region is located close to the sea further decides if and what type of sediments are available.
  - ○ Vegetation: Factors such as climatic conditions, precipitation, degree of the soil's fertility etc. decide on the type of vegetation and thereby which organic construction materials, i.e., timber, bamboo, thatch, are available.
- indigenous knowledge on traditional construction typologies:
  - ○ Indigenous knowledge of masons and craftsmen on traditional building technologies is heavily dependent on a region's cultural heritage and its ability to preserve traditions and cultural assets.
  - ○ Traditional building types, which are often constricted to a small local area, can be manifold, representing the identity of a certain tribe, folk or ethnical group.
  - ○ A large number of traditional building typologies from regions all over the world including Central Asia are provided by web-based databases, such as the World Housing Encyclopedia (EERI, www.world-housing.net).

- the region's state of development and access to more modern or engineering construction typologies as well as work materials:
  - ○ This involves whether the region is located in the proximity of larger cities or urban centers.

- socio-economic conditions:
  - ○ The socio-economic status of any person, family or any social entity is based on income, education and occupation; all these factors decide on a person's awareness (e.g. of natural hazards and risks) as well as ambitions to keep or improve living conditions.
  - ○ The higher the socio-economic status, the higher the standard of housing conditions including the houses' safety against natural hazards; this includes access to engineering services.
- weather and climatic conditions in general:
  - ○ Meteorological conditions such as precipitation (rain, snow), high-low temperatures, differences in temperature (day-night, summer-winter) influence the building typology in terms of choice of work materials, wall thicknesses, roof shape, insulation/isolation measures, etc.
- location:
  - ○ The location of a building or a village with respect to water bodies, topographic features (slopes) etc. has influence on the susceptibility of natural hazards and the occurrence of potential secondary effects (e.g. earthquake-induced liquefaction).
  - ○ Structural and architectural features of buildings are often governed by prevalent natural hazards referring to their proximity to river banks, active faults, slopes etc. Examples for these features

are the introduction of stilts above the maximally observed flood level, hybrid load-transfer systems, or the slope of pitched roofs.

○ A site's hazard history, i.e., how frequently natural hazards occurred in the past, may also impact prevalent construction typologies. Here, those building typologies prevail that have shown to perform well during past natural events. This may also lead to the incorporation of special structural features in order to improve the building's performance, e.g., the provision of ring beams or through-stones in masonry walls in order to prevent the wall's failure.

All these factors do not only have influence on local construction typologies in developing countries, but also in the developed world. Especially the scarcity of a certain work material, as e.g. the absence of timber in most parts of India due to deforestation during past decades, automatically affects its price and hence becomes economically unviable to use for common housing construction. On the other hand, local geological conditions may also strongly affect the type of wall units mostly applied in a certain region. The availability of clay may serve as a vivid example, as the majority of Indian housing stock ($>$ 80%; [19]) consists of burnt clay brick construction. The local availability and production of clay bricks across India keeps the unit price of bricks at moderate levels in most parts of the country. The same type of bricks are more than double the price in Bhutan where clay is mostly unavailable, i.e., unit price Indian Rs. 7.5 vs. Indian Rs. 17, respectively [26]. The gross difference in price solely results from the fact that bricks have to be imported into Bhutan and transported over long distances.

The prevalence of a building typology is, to a large extent, foremost governed by the local or at least regional availability of building materials, which is, largely dependent on geological conditions. Other factors, as described before, may then decide on the more peculiar features of a building typology, such as construction principle, wall thickness, roof types etc.

3. Application to Central and South Asian test beds

In the course of AKDN's risk reduction activities in Central and South Asia, a proper vulnerability assessment of existing facilities was conducted covering more than 5500 building and infrastructure facilities in Afghanistan, India, Kyrgyzstan, Pakistan and Tajikistan [6]. These facilities comprise a variety of occupancy purposes including schools, hospitals, health centers, community centers, offices, warehouses, as well as pure residential units. In the course of establishing this database, a building typology and vulnerability classification scheme was developed covering both engineered and non-engineered typologies that are prevalent not only in the five addressed countries but also in the whole Central and South Asian region.

3.1. Geological conditions

Fig. 1 provides an overview of the present study's test bed region of Central and South Asia. In order to qualitatively illustrate the region's seismic hazard, each country's seismic zoning map, as provided by the respective national seismic design code [14,35,29,34], is given in a simplified way based on macroseismic intensities [6]. Table 3 provides an overview of the geological conditions of the study's test bed region of Central and South Asia, while Fig. 2 shows the region's spatially distributed soil conditions represented by an average shear-wave velocity $V_{s,30}$ of the near-surface soil layers.

3.2. Socio-economic conditions

Judging from a socio-economic point of view, almost all South and Central Asian countries are still under development and even some regions may be called underdeveloped. Especially in Afghanistan and Pakistan where severe safety and security threats contribute to poor economic and social development. In view of the vast population numbers which are still rising and the diverse socio-economic conditions as well as a glaring imparity between the various social classes, India, though demonstrating a thriving economy, is still struggling to provide basic and essential amenities to the below poverty-level community. Both Tajikistan's and Kyrgyzstan's economies largely run on foreign remittances and are still struggling to open their economies to open markets.

3.3. Weather and climatic conditions

The prevalent weather and climatic conditions of a region strongly affect its construction typologies, especially in the case of informal non-engineered housing. Here, the occurrence of extreme precipitation may impact the materials and/or shape of roofs and walls, the way wall foundations are provided, or isolation solutions are added to the building. Table 4 lists the various climatic conditions and provides impacts on the main structural components of a building, i.e., wall, roof, and foundation.

3.4. Application of the proposed building classification scheme

The herein proposed building classification scheme was developed following a four-step procedure subsequently described:

1. *Sample building data collection*: The process of building classification commenced with collection of building types from the five countries addressed in this study. In total, more than 5400 building samples were collected and their predominant features analyzed (see Appendix 1). The AKDN facility database is the source for the sample data, which comprises of spatial information, type of buildings by occupancy, use and tenure, age, as well as principal dimensions (story number, height, footprint area). The database is further supported with photographs of façade views and structural drawings (e.g. plan shapes).
2. *Establish criteria for the classification and the definition of typologies:* Based on review of relevant practices that are previously referred to, the main criteria for building typology classification were decided. These criteria are (in a somewhat descending order of importance): primary load-bearing structural system, predominant work material for walls, details of wall material (e.g. type of brick mortar, unreinforced/reinforced/confined), flooring and roofing type. In principal, this scheme follows the various material classes as used by the EMS–98 classification scheme [12].
3. *Decision on the final Model Building Typologies (MBT's):* The classification criteria were tested on sample buildings and further revised when finalizing the building typology. Table 5 describes the proposed building typology classification for the Central and South Asian building stock defining 29 model building typologies (MBT) distributed over nine load-bearing systems. Illustrations of most of these MBT's are given in Fig. 3 while Table 6 provides information on these building typologies' prevalence in the respective regions. Further, the type of areas (urban, suburban, rural) are mentioned in which the building typologies can be found. To understand the characteristics of these typologies as well as to assign vulnerability information already elaborated or compiled for buildings of the same typology, each of the 29 model building typologies are categorized according to the most popular international building classification schemes (see Table 7). Structural, non-structural and socio-economic parameters for each MBT were chosen in close consultation with field professionals of each respective country, having insight on the future use of these facilities. The parameters assigned to each MBT include internationally accepted building taxonomy, predominant location, architectural and structural description, occupancy, photos and sketches of representative buildings, experienced damage patterns, and expected collapse probabilities.

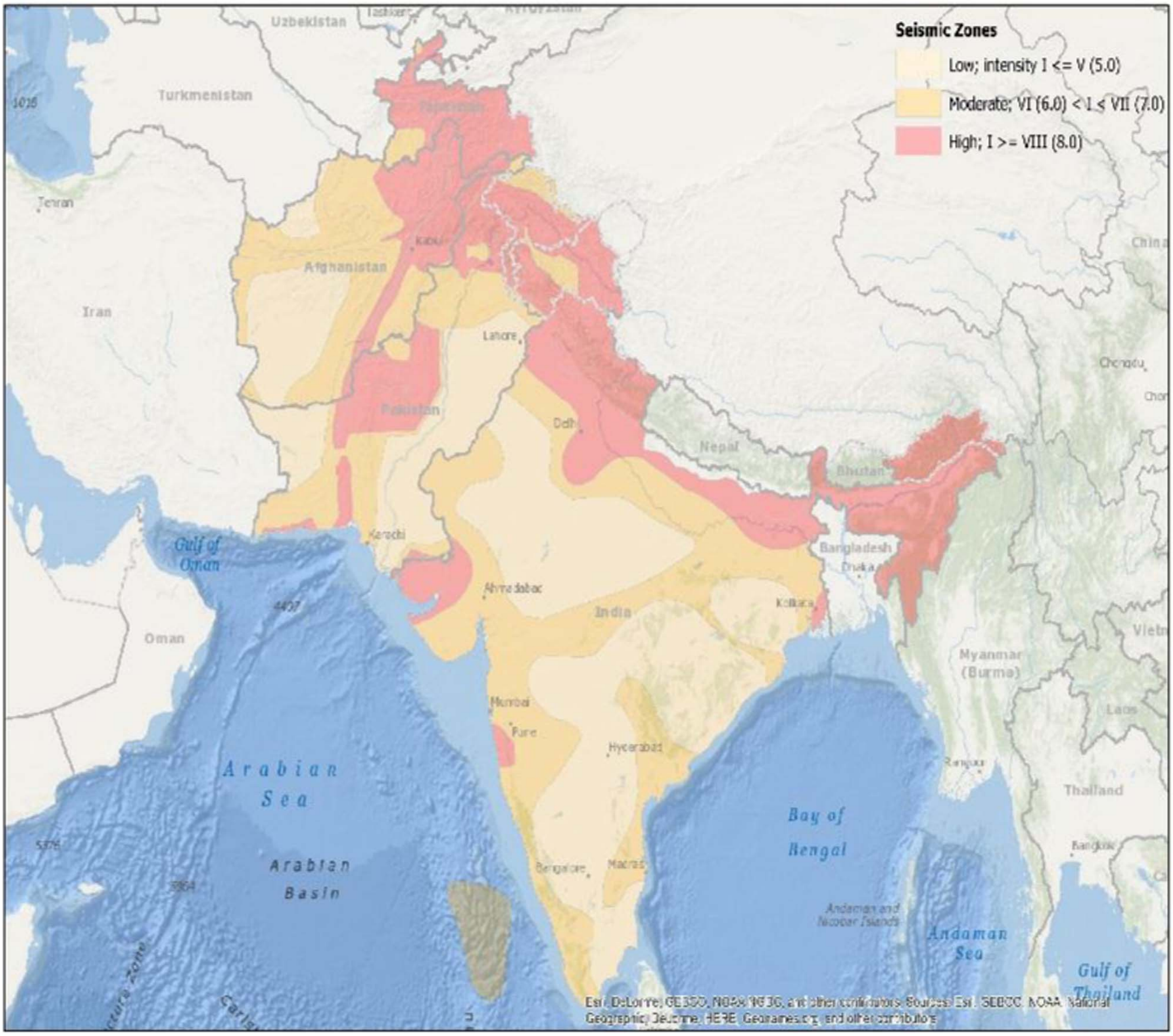


Fig. 1. Map showing the target region of Central and South Asian countries as well as a qualitative distribution of the various countries' seismic hazard [6].

4. *Establish a consistent vulnerability scale covering all MBT's*: The generation of a vulnerability scale for the defined MBT's may serve the purpose to set up a priority ranking for the implementation of future risk mitigation measures, i.e. structural improvements (retrofitting, strengthening), change of use, decommissioning, or the termination of lease agreements. While the scope of the present article is not to discuss the detailed methodology for defining the vulnerability scale, it may be added that the vulnerability assigned to a certain MBT is based upon a structural vulnerability score derived using a questionnaire form of 16 specific questions related to the various structural features of the building typology. These 16 questions address four categories, i.e. plan and elevation irregularity, structural configuration, past earthquake performance, and alternations. For the purpose of validating the vulnerability scores, an independent peer review process was carried out comprising of practicing earthquake engineers, university teachers and researchers, each having ample knowledge on building construction in Central and/or South East Asia. The final scale is presented in Table 8.

3.5. Correlation with results from empirical and theoretical-based vulnerability assessment

To get an idea about the reliability and applicability of the proposed visual screening-based vulnerability scale, the derived results are correlated with vulnerability estimates of both empirical and analytical procedures. Empirical vulnerability estimates are available in the World Housing Encyclopedia (WHE; www.world-housing.net), an open database on worldwide building typologies. The WHE database has been sighted with respect to the various building typologies existing in those countries addressed in this manuscript. It can be seen that the assigned vulnerability classes (VC) following EMS-98 [12] confirm the ranking of the vulnerability scores that is provided by the visual screening based vulnerability scale. In addition, the proposed visual screening-based vulnerability scale is correlated with results from one of the purely theoretical methods available in the literature. These methods are based on theoretical simulation of physical damage under earthquake loading. These theoretical methods analytically predict the structural damage that a building of a given capacity will experience under a given seismic

Table 3
Geological conditions of the study's test bed region of Central and South Asia.

Country	Sub-region	Geological Conditions	Predominant Building Material	Prevalent Construction Typologies
India	South and Central India	Deccan trap	Igneous rocks, Metamorphic rocks Weathered rocks Mud with high content of silica	● Heavy Stone undressed masonry ● Ashlar/Dressed Stone Masonry
	East-Central-West and North India	Gondwana and Vindhyan	Sedimentary rocks, Weathered rock Clay and alluvium deposit	● Mud masonry ● Stone Masonry ● Brick Masonry ● Timber/bamboo frame housing
Afghanistan	East-North-Central Afghanistan	Afghan North Pamir	Sedimentary and Metamorphic rocks Weathered rocks	● Stone masonry ● Mud/ Adobe masonry
	South-Central and West	South Afghanistan	Weathered Rock Clay and sandy soil	● Mud/ Adobe masonry
Pakistan	North	Paleozoic, Precambian, Late Mesozoic Early Tertiary	Metamorphic and Volcanic rock	● RR Stone masonry ● Dressed Stone ● Timber Frame structure ● Hybrid Masonry
	East-Central and West	Quaternary, Tertiary Volcanic, Mesozoic	Sedimentary Rocks Alluvium Deposit Clay	● Adobe / Mud masonry ● Brick masonry
Tajikistan	West and South	Pamir Plateau	Metamorphic and Sedimentary Rock	● Ashlar/Dressed Stone Masonry
	East, North and Central	Pamir Plateau	Sedimentary Rocks Alluvium Deposit Clay	● Adobe / Mud masonry ● Brick masonry

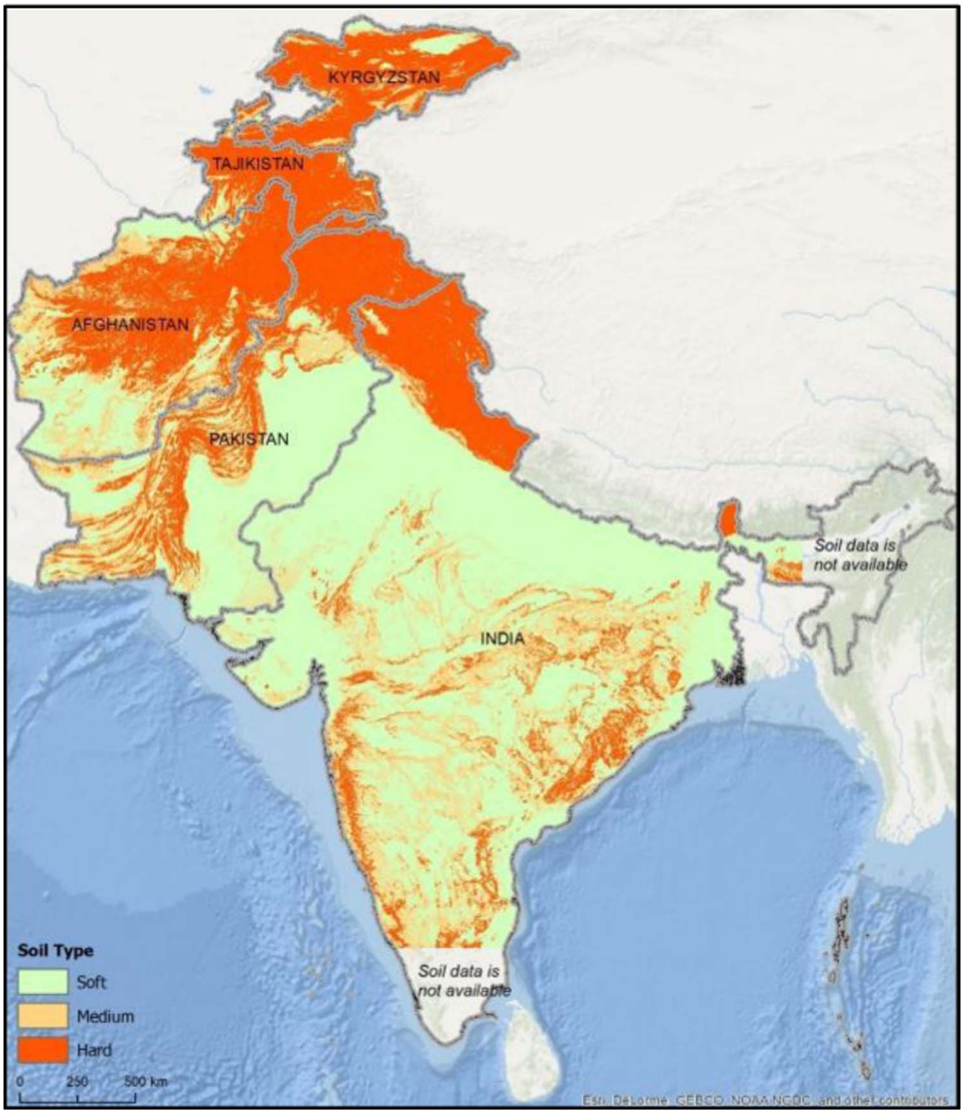


Fig. 2. Soil maps of South and Central Asian countries (based on $V_{S,30}$ soil classification).

Table 4
Impact of weather and climatic conditions on the main structural components of a building.

Climate condition	Climate Characteristics	Impact on wall	Impact on roof	Impact on foundation
Dry	● Characterized by a severe lack of precipitation, to the extent of hindering or preventing the growth and development of plants and animal life	● Large wall thicknesses to protect the interior from overheating ● Wall heights from 2.5 to 3.5 m ● Few window openings and low-height doors	● Low-rise single/double pitched roofs to protect from high wind, and thermal insulation ● Use of thick mud packs on the top to protect from heat ● Small roof overhangs ● Usual roof covers with clay tiles or locally available roof materials	● Spread footing foundation without water treatment ● The plinth level is closer to the ground level
Tropical	● Wet season (summer) and dry season (winter). ● During the wet season, temperature average about 25 °C. During the dry season, temperatures average about 20 °C. ● During the wet season, at least 65 cm rainfall	● Moderate thickness of wall (< 45 cm) ● Mud or cement plaster to protect from rain ● Adequate opening for ventilation	● Single or double pitched roof ● Large roof overhangs ● Water and thermal insulation of roof ● Dampness and water leakage are main problem for structural vulnerability	● Mostly spread footing foundation up to 1.5 m for single story ● The plinth level is above the ground level ● In water logging areas, houses are constructed on stilts
Mountain and High Land	● Extreme low and high (−40 °C to 45 °C) temperature ● No rain or scanty rain ● Less vegetation	● Heavy and thick walls to insulate from extreme temperatures ● Less number of openings ● Large usage of timber	● Flat or low inclined roofing predominant use of slates/ corrugated sheet / timber for roofing	● Construction of basement used for farm product storage or animal keeping ● Foundation is < than 60 cm

ground motion intensity parameter. Theoretical methods vary from simplified non-numerically-based analyses to nonlinear static and dynamic numerically-based analysis procedures of varying complexity and accuracy (Meslem et al., 2014; D'Ayala et al., 2015). Within the scope of the present study, the Capacity Spectrum-based method is selected, during which the building's vulnerability is expressed in terms of a capacity curve representing the nonlinear behavior of the structure under an incrementally increasing lateral displacement (FEMA 2000, EN 1998). The seismic ground motion (also expressed as the seismic demand) is represented by a response spectrum in terms of physical parameters, i.e. spectral accelerations S_a and spectral displacements S_d. The convolution between capacity curve and response spectrum leads to the identification of the target displacement (or performance point) representing the mean damage an individual building of the respective building typology class will experience. Finally, the performance point is used to estimate the damage ratio using the corresponding set of fragility functions (see Fig. 4).

The computation of seismic vulnerability (seismic performance and damage ratio) for the different building typologies is conducted selecting vulnerability models that had been originally derived for similar building typologies from different regions. To ensure a selection of models appropriate for the scope of this present study, a Relevance Ranking System, developed within the framework of the Global Earthquake Model (GEM), was followed in order to come up with a reliable earthquake loss assessment [23,27,5]. As a result of seismic risk-related research programs implemented in earthquake-prone regions (e.g. in developing prevention and mitigation actions, refine code provisions and guidelines, and also the insurance industries that have invested in developing earthquake catastrophe models etc.) there is now a wealth of seismic vulnerability models, covering a wide range of building typologies and portfolios, available in the literature. However, the main challenge in using these pre-defined physical vulnerability models is identifying suitable models to ensure a reliable earthquake loss assessment. Differences in construction techniques and detailing between different regions can sometimes be significant, even when buildings are nominally designed according to similar code provisions; hence, it may introduce a certain level of uncertainty in the risk assessment process. Furthermore, these existing models have been derived using a variety of approaches, assumptions and methodologies that employ diverse structural modelling and analysis techniques (as discussed in the previous Section). A range of sampling methods has also been applied to parameters of the structural models and the seismic demand in order to account for uncertainties and intrinsic differences observable in the building stock and its response to seismic loading. It can therefore be difficult to appraise existing physical vulnerability models, even when derived for the same structural typology class.

The main idea of the Relevance Ranking System (which is a result of a sensitivity analysis of the different parameters influencing the development of physical vulnerability models) is to assist seismic risk analysts in appropriately selecting and making use of these existing vulnerability models for future applications. This especially when studies are conducted for large portions of the building stock (and hence use the existing models to reduce the calculation efforts), or because of lack of available resources or lack of information which does not allow for a detailed survey and data acquisition (i.e. to develop customized functions that address the peculiar structural and non-structural characteristics of the respective building stock). The rating system considers three main attributes (see Fig. 5):

- Size and regional attribute: to consider the level of the assessment, i.e., on an individual building/facility level, city level, country or global level;
- Defining structural system and classification modelling: to consider the representativeness of the structural system, ensuring an appropriate definition of the building classification; and
- Method of analysis and generating process used in correlating

Table 5
Description of 29 building typology classes assigned for Central and South Asia.

No.	Load-bearing system	Building typology	
		Index	Description
1	Stone masonry walls	SM − 1	Random rubble/field pebbles/stones in mud/lime mortar with timber/GI roof
2		SM − 2	Dry-packed stone walls with timber/GI roof
3		SM − 3	Unreinforced stone masonry wall with RCC floor/roof and timber/GI top roof
4		SM − 4	Unreinforced stone masonry wall, column/post and beam/band with wooden/GI roof
5	Mud (adobe) walls	AM − 1	Mud wall with timber/GI roof
6		AM − 2	Mud wall with beam/bands and columns/post, and timber/GI roof
7		AM − 3	Adobe brick wall with timber/GI roof
8		AM − 4	Compacted/rammed earth block walls with timber roof
9	Burnt clay brick masonry	BM − 1	Unreinforced brick masonry wall with wooden/GI roof
10		BM − 2	Unreinforced brick masonry wall with column/post and beams/bands with wooden/GI roof
11		BM − 3	Unreinforced brick masonry wall in cement mortar with RCC roof
12		BM − 4	Unreinforced brick masonry wall with lintel band and RCC roof
13		CM − 1	Confined masonry wall with concrete columns and beams roof with RCC roof
14	Concrete block masonry walls	CM − 2	Unreinforced block masonry, in lime/cement mortar, lintel bands with RCC floor/roof and top GI roof
15		CM − 3	Reinforced block masonry, in lime/cement mortar, lintel bands with RCC floor/roof and top GI roof
16	RC moment-resistant frames	MRCF − 1	MRF designed for gravity loads
17		MRCF − 2	MRF designed with seismic features
18		MRCF − 3	MRF with unreinforced masonry infill walls
19		MRCF − 4	MRF with concrete shear walls
20	RC shear walls	SWC − 1	RC walls cast-in-situ
21		SWC − 2	RC precast wall panel structure
22	Steel moment-resistant frames	MRSF − 1	MR steel frame with brick partition wall
23		MRSF − 2	MR steel frame with cast-in-situ concrete wall
24		MRSF − 3	MR steel frame with light-weight concrete wall
25	Light metal frames	LMF − 1	LM frame structure (single story)
26	Load-bearing timber frames	LBTF − 1	Timber post and beam frame
27		LBTF − 2	Timber frame with masonry infills
28		LBTF − 3	Timber frame with plywood/gypsum board sheathing
29		LBTF − 4	Timber frame with stud walls

physical damage with the ground motion intensity.

The level of uncertainty to be associated to the vulnerability model selection process of the ranking system will depend upon the condition under which the selected vulnerability models are used, i.e. the level of assessment and the application scope. In Fig. 5, the uncertainty to be associated with the vulnerability model selection process is measured in a qualitative way in form of guidance to users on how (under a given condition and for a given case study) to better select a suitable vulnerability model, and hence, lower the level of the expected uncertainty.

The total uncertainty to be associated to each result of the risk assessment is a combination of the uncertainties related to the vulnerability selection process and the uncertainties that are inherent to the individual steps of the vulnerability development process.

Table 9 provides parameter values of the vulnerability models, in terms of capacity curves and fragility functions, selected for each structural typology of the building stock identified in the study area. Fig. 6 illustrates an example for a seismic vulnerability model (capacity and fragility curves) customized for building typology class RCF1.1 L.

The damage matrix and damage ratio from the theoretical-based procedure, computed for each building type in the study's test bed region of Central and South Asia, can be seen in Table 7. Fig. 7 illustrates the comparison of the resulted visual screening-based vulnerability scale with the theoretical-based vulnerability estimation for the different building typologies. The comparison shows a good overall agreement between the vulnerability scale (qualitative estimation) developed within the present study and the results of the damage ratio (quantitative estimation) derived from the theoretical-based method. This observation can be more clearly seen in the case of building classes with high to very high vulnerability.

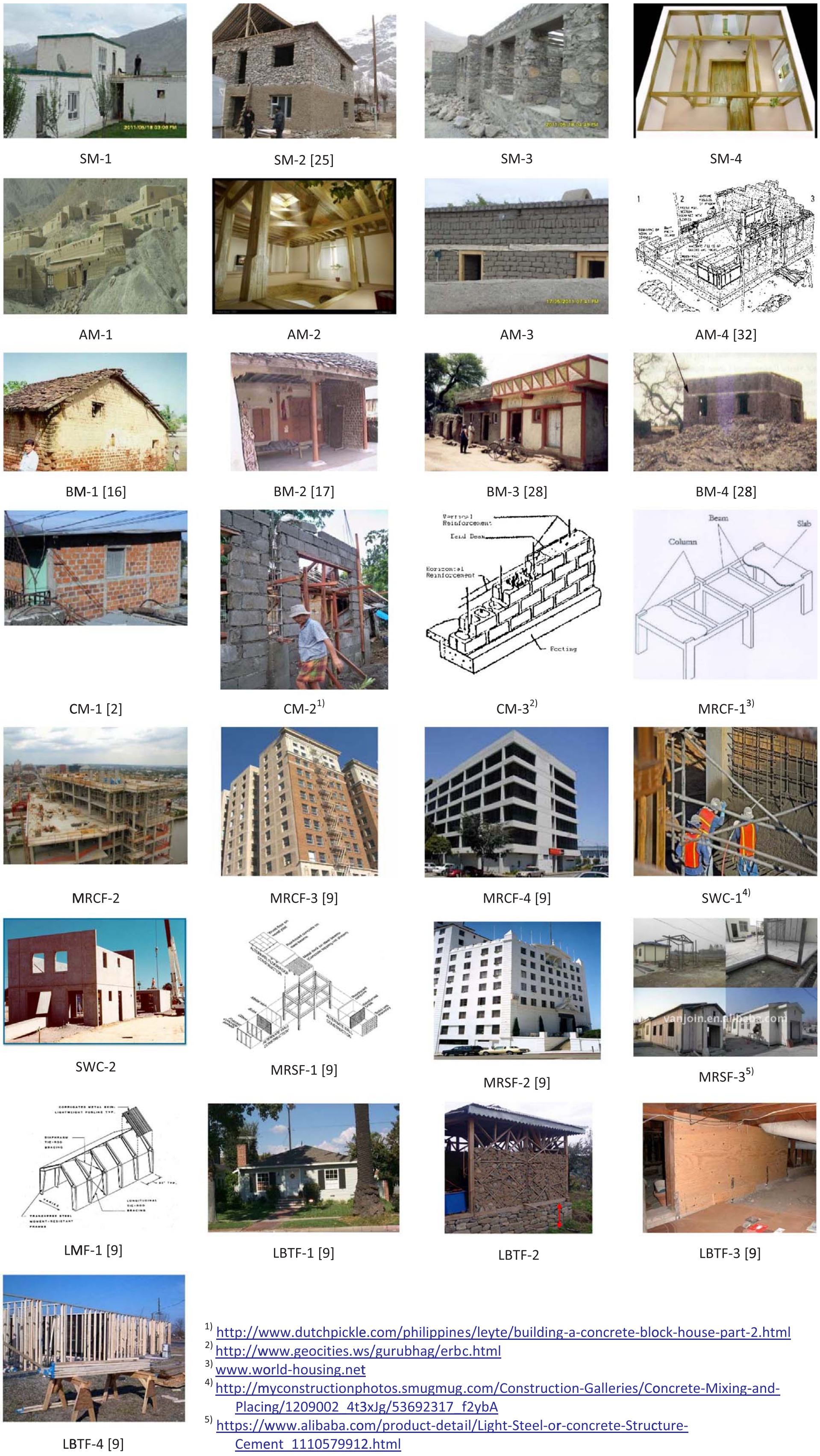
4. Conclusions

The main purpose of the present manuscript is to introduce an easy-to-use scheme with acceptable level of accuracy for a customized visual screening-based building typology and vulnerability classification. The classification scheme uses certain criteria based on data analysis from field surveys related to the geometric characteristics, the structural system of the building, local geological conditions, socio-economic conditions, and climate conditions. Within the scope of the present article, the considered target regions are the Central Asian countries Tajikistan and Kyrgyzstan, and the South Asian countries Afghanistan, India and Pakistan.

In order to examine the applicability of the proposed visual screening-based vulnerability scale, correlation studies have been conducted considering the results from theoretical-based vulnerability assessment procedure.

The proposed building vulnerability classification scheme has a large number of applications, some of which are:

- Vulnerability Assessment: The proposed classification scheme covers almost all types of vernacular to engineering construction prevalent in South to Central Asia. It is already applied for rapid visual screening of functional structures across the entire region.
- Incentivize structural improvement and mitigation: Referring to discussions with various stakeholders, there is a need for introducing an incentive-based promotion of structural improvement and mitigation measures. The classification is being used to assess structural and non-structural vulnerability of households in eastern Tajikistan. Based on the vulnerability and risk assessment, the structural improvement options are being worked out and the development of loan products are under way.



SM-1 SM-2 [25] SM-3 SM-4

AM-1 AM-2 AM-3 AM-4 [32]

BM-1 [16] BM-2 [17] BM-3 [28] BM-4 [28]

CM-1 [2] CM-2[1] CM-3[2] MRCF-1[3]

MRCF-2 MRCF-3 [9] MRCF-4 [9] SWC-1[4]

SWC-2 MRSF-1 [9] MRSF-2 [9] MRSF-3[5]

LMF-1 [9] LBTF-1 [9] LBTF-2 LBTF-3 [9]

LBTF-4 [9]

Fig. 3. Building types and their features [2,9,16,17,25,28,32].

[1] http://www.dutchpickle.com/philippines/leyte/building-a-concrete-block-house-part-2.html

[2] http://www.geocities.ws/gurubhag/erbc.html

[3] www.world-housing.net

[4] http://myconstructionphotos.smugmug.com/Construction-Galleries/Concrete-Mixing-and-Placing/1209002_4t3xJg/53692317_f2ybA

[5] https://www.alibaba.com/product-detail/Light-Steel-or-concrete-Structure-Cement_1110579912.html

Table 6

Availability of the 29 building typology classes in the various regions in Central and South Asia (sample distribution in percentages) provided in terms of shares of the total building stock as well as information on areas of distribution (urban, suburban, rural).

No.	Load-bearing system	Building typology Index	India				Afghanistan				Pakistan				Tajikistan			
			South and Central (3%)		East-Central-West and North (13%)		East-North-Central (5%)		South-Central and West (4%)		North (55%)		East-Central and West (16%)		West and South (2%)		East, North and Central (2%)	
1	Stone masonry walls	SM-1	●●●	R	●●●	R	●●	R	●	R	●●●	R	●	R	–		●●	SR
2		SM-2	–		●	R	●	R	●	R	●●●	R	●	R	–		●●	SR
3		SM-3	●●	SR	●●	SR	●●	SR	●	SR	●●●	SR	●	SR	●	R	●	S
4		SM-4	–		●●	SR	●●	R	–		●●●	U	●	U	–		●●●●	SR
5	Mud (adobe) walls	AM-1	●●	R	●●	R	●●●	SR	●●●	R	●	R	●●●	R	●●	R	●	R
6		AM-2	–		●	R	●	R	–		●	R	●●●	R	–		●	R
7		AM-3	–		●	SR	●●●	SR	●●●	SR	●	SR	●	SR	●●●	SR	●●	R
8		AM-4	–		–		●	R	●	R	●	R	–		–		–	
9	Burnt clay brick masonry	BM-1	●●	SR	●●●	SR	●	SR	●	SR	–		●●	SR	●	SR	–	
10		BM-2	●●	RSU	●●	RSU	–		–		●	SU	●●	SU	–		–	
11		BM-3	●●	SU	●●	SU	●●	SU	●●●	SU	●●	SU	●●	SU	●●●	SU	●	S
12		BM-4	●●●	SU	●●●	SU	●●	SU	●●	SU	●	SU	●●●	SU	●●	SU	●	S
13		CM-1	●●	SU	●●	SU	●●	SU	●●●	SU	●●	SU	●●●	SU	●●	SU	●●	S
14	Concrete block masonry walls	CM-2	●●	SU	●●	SU	●●	SU	●●	SU	●	SU	●●	SU	●●	SR	●	S
15		CM-3	●●	SU	●●	SU	●●	SU	●	SU	●	SU	●●	SU	–		–	
16	RC moment-resistant frames	MRCF-1	●●	SU	●●	SU	●	SU	●	U	●	SU	●●●	SU	–		–	
17		MRCF-2	●●	SU	●	SU	●●	U	●●●	U	●	SU	●	SU	●●	SU	●●	S
18		MRCF-3	●	SU	●	SU	●	U	●	U	●	SU	●	SU	●	U	●	S
19		MRCF-4	●	SU	●	SU	●●	U	●	U	●	SU	●	SU	●●●	U	●	S
20	RC shear walls	SWC-1	●	U	●	U	●	U	●●	U	●	U	●	U	●●	U	●	S
21		SWC-2	–		–		–		●	U	–		–		●●●●	U	●●	S
22	Steel moment-resistant frames	MRSF-1	–		–		●	U	●	U	–		–		●	U	–	
23		MRSF-2	–		–		–		–		–		–		–		–	
24		MRSF-3	–		–		–		●	U	–		–		●	U	–	
25	Light metal frames	LMF-1	●	U	●	U	●	U	●	U	●	U	●	U	●	U	●	S
26	Load-bearing timber frames	LBTF-1	–		●	R	●	R	●	SU	●	R			●	SU	●	S
27		LBTF-2	–		●	R	●	R	–		●	R	–		–		–	
28		LBTF-3	–		●	R	●	R	–		●	R	–		–		–	
29		LBTF-4	–		●	R	●	R	–		●	R	–		–		–	

with:	●●●●	prevalent	(share of building stock > 70 %)
	●●●	frequently/common	(share of building stock 30 – 70 %)
	●●	regularly observed	(share of building stock 5 – 30 %)
	●	sparsely observed	(share of building stock < 5 %)
	–	not available	
	R	rural	
	S	suburban	
	U	urban	

Table 7
Building typologies and their categorization according to various global and international classification schemes.

Index	Wall/frame type	Flooring type	Roof type	*N*[a]	Building typology class acc. to									
					PAGER–STR[b]	*PAGER–STR description*	*GEM Taxonomy Shorthand Form*[c]	*GEM Description*	*EMCA*[d]	*HAZUS*[e]	*Risk–UE*[f]	*PSI*[g]	*EMS*[h]	*WHE*[i]
SM-1	Random (Rubble / Field / Pebble) Stones in Mud/Lime mortar	wood	timber/GI	1 ([b]	RS2	Local field stones with mud mortar	MUR + STRUB + MOM/LWAL/	Masonry unreinforced wall; Rubble (field stone) or semi-dressed stone; Mud mortar.	EMCA-1.1	–	(M1.[a]	AR1	M1	1
					RS3	Local field stones with lime mortar	MUR + STRUB + MOL/LWAL/	Masonry unreinforced wall; Rubble (field stone) or semi-dressed stone; Lime mortar.	EMCA-1.1	–	(M1.[a]	AR1	M1	–
SM – 2	Dry-packed stone (no mortar)	wood	timber/GI	1 ([b]	RS1	Local field stones dry stacked (no mortar) with wood floors (joists), earth, or metal roof	MUR + STRUB + MON/LWAL/RME + RME99/FME + FME1/	Masonry unreinforced wall; Rubble (field stone) or semi-dressed stone; No mortar; Metal (unknown) roof; Metal beams or trusses supporting light.	–	–	(M1.[a]	–	(M[c]	1
SM – 3	Unreinforced stone masonry	RC	RC	1–2	RS5	Local field stones with cement mortar and reinforced concrete bond beam	MR + RCB + STRUB + MOC/LWAL/	Masonry unreinforced wall; Rubble (field stone) or semi-dressed stone; Cement mortar + reinforced concrete bands.	EMCA – 1.2	–	(M1.[a]	–	(M[c]	–
SM – 4	Unreinforced stone masonry with column/post and beam/band	wood	timber/GI	1–2	–	–	–	–	EMCA – 1.4	–	–	–	(M[c]	–
AM – 1	Mud wall	wood	timber/GI	1–2	M1	Mud walls without horizontal wood elements	EU + ET99/LWAL/	Earth unreinforced (unknown) wall	EMCA – 4.1	–	–	–	–	3
AM – 2	Mud wall with beam/ band and column/ post	wood	timber/GI	1–2	M2	Mud walls with horizontal wood elements	ER + ET99 + RW/ LWAL/	Earth reinforced wood (unknown) wall	EMCA – 4.1	–	–	–	–	4
AM – 3	Adobe brick wall	wood	timber/GI	1–2	A1	Adobe block, mud mortar, wood roof and floors	MUR + ADO + MOM/ LWAL/RW + RW99/ FW + FW99/	Masonry unreinforced wall; adobe blocks; mud mortar; wood roof (unknown); wood floor (unknown)	EMCA – 4.1	–	M2	AA1	M2	5
AM – 4	Compacted/Rammed earth block wall	wood	timber/GI	1–2	RE	Rammed Earth/Pneumatically impacted stabilized earth	EU + ETR/LWAL/	Earth unreinforced wall; Rammed earth	EMCA – 4.1	–	(M[b]	AE1	(M[b]	6
BM – 1	Unreinforced brick masonry wall	wood	timber/GI	1–2	UFB1	Unreinforced brick masonry in mud mortar without wood posts	MUR + CLBRS + MOM/LWAL/	Masonry unreinforced wall; fired clay solid bricks; mud mortar	EMCA – 1.1	–	M3.1	–	(M[e]	7
					UFB3	Unreinforced brick masonry in lime mortar	MUR + CLBRS + MOL/ LWAL/	Masonry unreinforced wall; fired clay solid bricks; lime mortar	EMCA – 1.1	–	M3.2	–	(M[e]	–
BM – 2	Unreinforced brick masonry wall with column/post and beam/band	wood	timber/GI	1–2	UFB2	Unreinforced brick masonry in mud mortar with wood posts	MUR + CLBRS + MOM/LWAL/	Masonry unreinforced wall; fired clay solid bricks; mud mortar	EMCA – 1.1	–	M3.1	–	(M[e]	8
					UFB4	Unreinforced fired brick masonry, cement mortar. wood flooring, wood or steel beams and columns, tie courses (bricks aligned perpendicular to the plane of the wall)	MUR + CLBRS + MOC/ LWAL/-/FW99/	Masonry unreinforced wall; fired clay solid bricks; cement mortar; wood floor (unknown)	EMCA – 1.1	–	M3.3	BB1	(M[e]	–
BM – 3	Unreinforced brick masonry wall in cement mortar	RC	RC	1–3	UFB5	Unreinforced fired brick masonry, cement mortar, but with reinforced concrete floor and roof slabs	MUR + CLBRS + MOC/ LWAL/RC + RC99/ FC + FC99/	Masonry unreinforced wall; fired clay solid bricks; cement mortar; concrete roof (unknown); concrete floor (unknown)	EMCA – 1.2	–	M3.4	–	M6	9

(*continued on next page*)

Table 7 (*continued*)

Index	Wall/frame type	Flooring type	Roof type	*N*[a]	Building typology class acc. to									
					PAGER–STR[b]	*PAGER–STR description*	*GEM Taxonomy Shorthand Form*[c]	*GEM Description*	*EMCA*[d]	*HAZUS*[e]	*Risk–UE*[f]	*PSI*[g]	*EMS*[h]	*WHE*[i]
BM – 4	Unreinforced brick masonry wall with lintel band	RC	RC	1–4	–	–	–	–	EMCA – 1.4	–	(M3.[d]	–	(M[f]	–
CM – 1	Confined masonry wall with concrete columns/beams	RC	RC	1–4	RM3	Confined masonry	MCF + MUN99/ LWAL/	Confined masonry (unknown unit) wall	EMCA – 1.3	–	M4	BB2	M7	10
CM – 2	Unreinforced block masonry in lime/ cement mortar, lintel bands	RC	RC/GI	1–2	UCB	Unreinforced concrete block masonry with lime or cement mortar	MUR + CB99 + MOC/ LWAL/	Masonry unreinforced wall; concrete blocks; cement mortar	EMCA – 1.4	–	(M3.[d]	BC1	M5	11
CM – 3	Reinforced block masonry in lime/ cement mortar, lintel bands	RC	RC/GI	1–2	–	–	–	–	EMCA – 1.4	RM2	–	–	(M[g]	–
MRCF – 1	Moment-resisting RC frames designed for gravity loads only (pre-code)	RC	RC	1–2	C4	Nonductile reinforced concrete frame without masonry infill walls	CR + CIP/LFM + ND/	Concrete reinforced; cast-in-place; moment frame; nonductile	EMCA – 2.1	–	(RC[c]	CC1	RC1	14
MRCF – 2	MR RC frames designed for seismic features	RC	RC	1–3	C1	Ductile reinforced concrete moment frame with or without infill	CR + CIP/LFM + DU/	Concrete reinforced; cast-in-place; moment frame; ductile	–	(C[a]	(RC[a]	DC1	RC3	15
MRCF – 3	MR RC frames with unreinforced masonry infill walls	RC	RC	2–5	C3	Nonductile reinforced concrete frame with masonry infill walls	CR + CIP/LFINF + ND/	Concrete reinforced; cast-in-place; infill frame; nonductile	EMCA – 2.3	C3	RC31	DC2	RC2	16
MRCF – 4	MR RC frames with concrete shear walls (hybrid system)	RC	RC	1–2	C6	Concrete moment resisting frame with shear wall - dual system	CR + CIP/LDUAL/	Concrete reinforced; cast-in-place; dual system	EMCA – 2.2	–	RC4	DC3	–	19
SWC – 1	RC shear walls	RC	RC		C2	Reinforced concrete shear walls	CR + CIP/LWAL + D99/	Concrete reinforced; Cast-in-place; Wall; Ductility unknown.	EMCA – 2.4	C2	RC2	–	RC6	21
SWC – 2	RC precast wall panel structure	RC	RC	2–9	PC4	Precast panels (wall panel structure)	CR + PC/LWAL/	Concrete reinforced; precast concrete; wall	EMCA – 3	–	RC5 (RC[f]	DP3	–	22
MRSF – 1	Moment Resisting Frame				S5	Steel frame with unreinforced masonry infill walls	S/LFINF/	Steel;Infill frame.	EMCA – 6	S5	S3	DS3	S	23
MRSF – 2	Dual frame-wall system				S4	Steel frame with cast-in-place concrete shear walls	CR + CIP/LWAL/	Concrete reinforced; Cast-in-place; Wall.	EMCA – 6	S4	S4	DS5	S	24
MRSF – 3	Dual frame-light-weight wall								EMCA – 6				S	
LMF – 1	Light Metal frame (single story)				S1	Steel moment frame	S/LFM/	Steel;Moment frame.	EMCA – 6	S1	S1	DS2	S	25

(*continued on next page*)

Table 7 (*continued*)

Index	Wall/frame type	Flooring type	Roof type	*N*[a]	Building typology class acc. to									
					PAGER–STR[b]	*PAGER–STR description*	*GEM Taxonomy Shorthand Form*[c]	*GEM Description*	*EMCA*[d]	*HAZUS*[e]	*Risk–UE*[f]	*PSI*[g]	*EMS*[h]	*WHE*[i]
LBTF – 1	Timber post and beam frame	wood	timber/GI	1–2	W3	Light post and beam wood frame. The floors and roofs do not act as diaphragms. No bracing, poor seismic load resistance path with poor connections. Wood frame may have partial infill walls with or without wood cladding.	W + WLI/LPB/RWO + RWO99/	Wood; Light wood members; Post and beam.	EMCA – 5.1	–	W	CT1	T	28
					W6	Unbraced heavy post and beam wood frame with mud or other infill material. Un-braced wood frame with connections meant to resist (gravity) vertical loads only. Floors or roof consists of wood purlins supporting thatched roof, wood planks or rafters supporting clay tiles.	W + WH/lWAL/RWO + RWO2/	Wood; Heavy wood; Wall.	EMCA – 5.2	–	W	–	T	29
LBTF – 2	Timber frame with masonry walls	wood	timber/GI	1–2	W7	Braced wood frame with load-bearing infill wall system	–	–	EMCA – 5.1	–	W	–	T	31
LBTF – 3	Timber frame with plywood/ gypsum board sheathing	wood	timber/GI	1–2	W1	Wood stud-wall frame with plywood/gypsum board sheathing. Absence of masonry infill walls. Shear wall system consists of plywood or manufactured wood panels. Exterior is commonly cement plaster ("stucco"), wood or vinyl planks, or aluminum planks (in lower cost houses). In addition, brick masonry or stone is sometimes applied to the exterior as a non-load-bearing veneer. The roof and floor act as diaphragms to resist lateral loading. (US & Canadian single family homes).	W + WLI/LWAL/RWO + RWO3/	Wood; Light wood members; Wall.	EMCA – 5.1	W1	W	–	T	32
LBTF – 4	Timber frame with stud walls	wood	timber/GI	1–3	–	–	–	–	EMCA – 5.1	–	W	–	T	–

[a] *N* – range of stories (number of floors).
[b] Jaiswal and Wald [15].
[c] Brzev et al. [3].
[d] Wieland et al. [36].
[e] FEMA [10].
[f] Lungu et al. [21], Milutinovic and Trendafiloski [24].
[g] Spence et al. [30], Coburn and Spence (2002).
[h] Grünthal [12].
[i] EERI/IAEEs World Housing Encyclopedia (http://www.world-housing.net).

Table 8
Building classification and vulnerability scale for the existing building stock in the study's test bed region of Central and South Asia.

Material	Type of LB Structures	Index	Visual Screening-based Vulnerability Scale (qualitative)					Assigned Vulnerability Classes (VC) of building typologies included in the WHE database						Theoretical-based vulnerability (quantitative) computed for PGA=0,25g					
			Very Low	Low	Fair	High	Very High	VC (EMS-98)1)						No Damage	Slight Damage	Moderate Damage	Severe Damage	Complete Damage	Damage Factor
			🟦🟦🟦🟦🟦	🟩🟩🟩🟩🟩	🟨🟨🟨🟨🟨	🟧🟧🟧🟧🟧	🟥🟥🟥🟥🟥	A	B	C	D	E	F	🟦	🟦	🟨	🟧	🟥	
Masonry Construction	Stone Masonry Wall	SM-1	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	III						0.20	4.36	6.05	11.83	77.56	93.9
		SM-2	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥⬜⬜⬜	I						0.23	10.44	11.83	16.95	60.56	84.3
		SM-3	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥⬜⬜⬜⬜							0.39	9.20	13.81	18.86	57.73	84.0
		SM-4	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧⬜⬜⬜	⬜⬜⬜⬜⬜							0.39	13.81	18.86	11.90	55.03	76.0
	Mud/ Adobe Wall	AM-1	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥⬜⬜	III						0.23	10.44	16.95	11.83	60.56	80.6
		AM-2	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧⬜⬜⬜⬜	⬜⬜⬜⬜⬜	I	I					0.39	12.37	11.74	17.76	57.73	82.4
		AM-3	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧⬜⬜⬜⬜	⬜⬜⬜⬜⬜	I						0.39	13.81	18.86	11.90	55.03	76.0
		AM-4	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧⬜⬜⬜⬜	⬜⬜⬜⬜⬜	I						0.39	16.79	20.78	12.04	50.00	71.8
	Burnt Clay Brick / Block Wall	BM-1	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥🟥🟥🟥🟥	🟥⬜⬜⬜⬜	I	III					0.87	17.76	19.89	11.48	50.00	71.0
		BM-2	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧⬜⬜⬜⬜	⬜⬜⬜⬜⬜		I	II				0.87	17.76	19.89	11.48	50.00	71.0
		BM-3	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧⬜⬜	⬜⬜⬜⬜⬜	II	I					0.71	18.38	20.62	11.64	48.65	70.1
		BM-4	🟨🟨🟨🟨🟨	🟨🟨🟨🟨🟨	🟨🟨🟨🟨⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜			I				1.70	53.22	21.70	6.49	16.89	35.5
		CM-1	🟨🟨🟨🟨🟨	🟨🟨🟨🟨🟨	🟨🟨⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜							2.61	46.02	22.14	7.54	21.68	41.0
	CB Masonry	CM-2	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧⬜⬜⬜⬜	⬜⬜⬜⬜⬜							0.71	18.38	20.62	11.64	48.65	70.1
		CM-3	🟨🟨🟨🟨🟨	🟨🟨🟨🟨🟨	🟨⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜							0.87	22.43	22.01	11.35	43.34	65.2
Reinforced Concrete	Moment Resistant Frame	MRCF-1	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧🟧🟧	🟧🟧🟧⬜⬜	⬜⬜⬜⬜⬜	I	I	II				0.71	20.16	21.47	11.60	46.07	67.9
		MRCF-2	🟩🟩🟩🟩🟩	🟩🟩🟩🟩⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜			I				1.48	33.50	23.46	9.83	31.73	53.1
		MRCF-3	🟨🟨🟨🟨🟨	🟨🟨🟨🟨🟨	🟨🟨🟨🟨⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜			I				10.98	15.93	63.72	2.41	6.96	31.9
		MRCF-4	🟩🟩🟩🟩🟩	🟩🟩🟩🟩⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜			I				9.29	61.37	21.14	2.25	5.95	20.3
	Shear wall Structure	SWC-1	🟩🟩🟩🟩🟩	🟩🟩⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜					I		18.83	78.53	1.85	0.17	0.63	7.7
		SWC-2	🟨🟨🟨🟨🟨	🟨🟨🟨🟨🟨	🟨⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜					III		22.14	46.02	21.68	7.54	2.61	21.4
Steel	Moment Resistant Frame	MRSF-1	🟨🟨🟨🟨🟨	🟨🟨🟨🟨🟨	🟨⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜							14.93	58.72	11.98	11.96	2.41	23.7
		MRSF-2	🟩🟩🟩🟩🟩	🟩🟩🟩🟩⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜							26.14	46.02	17.68	7.54	2.61	20.1
		MRSF-3	🟩🟩🟩🟩🟩	🟩🟩⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜							15.93	63.72	10.98	6.96	2.41	18.5
	LM Frame	LMF-1	🟦🟦🟦🟦🟦	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜							47.52	49.12	2.08	0.23	1.04	5.9
Wooden Structure	Load Bearing Timber Frame	LBTF-1	🟩🟩🟩🟩🟩	🟩🟩🟩⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜							13.93	53.72	12.98	16.96	2.41	28.8
		LBTF-2	🟨🟨🟨🟨🟨	🟨🟨🟨🟨🟨	🟨🟨⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜		I					9.29	71.37	11.14	2.25	5.95	17.8
		LBTF-3	🟩🟩🟩🟩🟩	🟩🟩🟩⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜							63.72	15.93	10.98	6.96	2.41	14.7
		LBTF-4	🟩🟩🟩🟩🟩	🟩🟩🟩⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜	⬜⬜⬜⬜⬜							18.83	78.53	1.85	0.17	0.63	7.7

1) bars indicate the number of individual reports included in the World Housing Encyclopedia addressing the respective building typology; gray shading indicates the most likely vulnerability class.

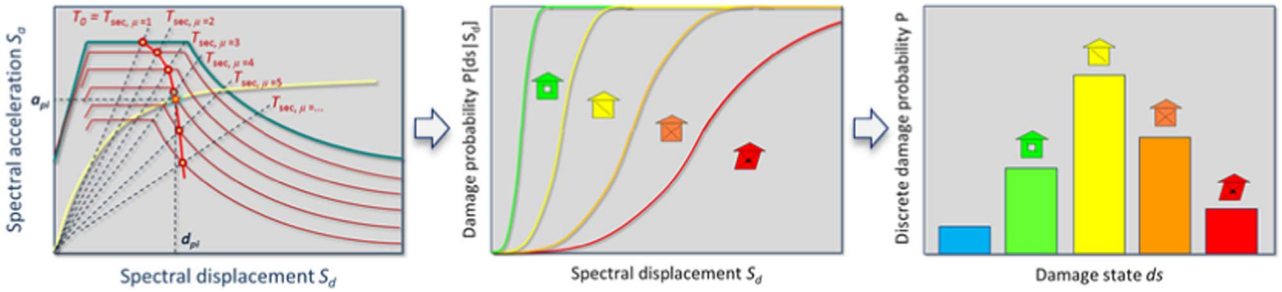


Fig. 4. Principle steps of the selected theoretical-based procedure for the calculation of seismic performance and damage ratio (quantitative seismic vulnerability).

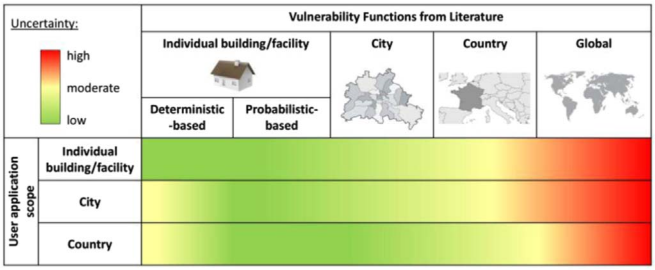
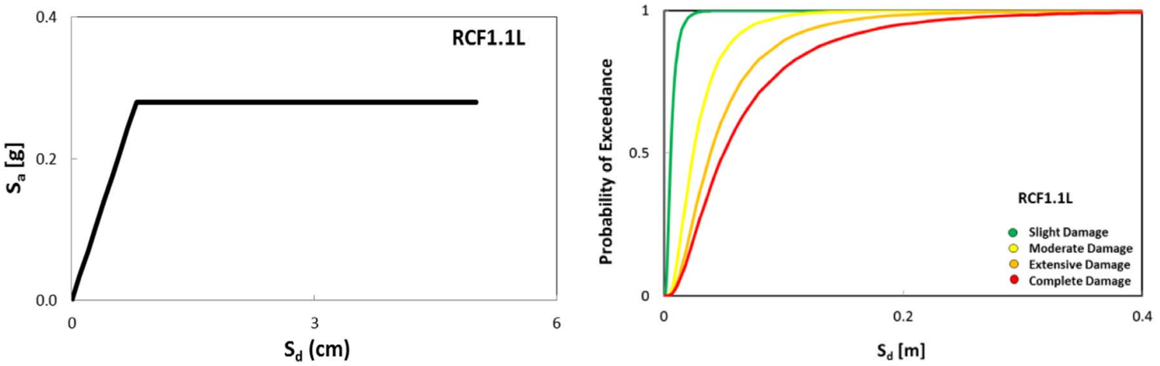


Fig. 5. Seismic vulnerability models selection framework considering size and regional factor and their uncertainties.

Table 9
Parameters of the selected vulnerability models (capacity curves and fragility functions for each damage state) assigned for each building typology.

Index	Capacity				Fragility Functions							
	$S_{d,y}$	$S_{a,y}$	$S_{d,u}$	$S_{a,u}$	Slight Damage		Moderate Damage		Extensive Damage		Complete Damage	
	[m]	[g]	[m]	[g]	Median [m]	β_{SD}	Median [m]	β_{MD}	Median [m]	β_{ED}	Median [m]	β_{CD}
SM − 1	0.005	0.170	0.017	0.170	0.0035	0.6557	0.0097	0.6791	0.0144	0.7537	0.0170	0.8332
SM − 2	0.005	0.180	0.017	0.180	0.0035	0.6557	0.0097	0.6791	0.0144	0.7537	0.0170	0.8332
SM − 3	0.005	0.190	0.018	0.190	0.0035	0.6557	0.0092	0.6791	0.0136	0.7537	0.0180	0.8332
SM − 4	0.005	0.210	0.018	0.210	0.0035	0.6557	0.0097	0.6791	0.0144	0.7537	0.0180	0.8332
AM − 1	0.005	0.210	0.017	0.210	0.0035	0.6557	0.0092	0.6791	0.0136	0.7537	0.0170	0.8332
AM − 2	0.005	0.250	0.019	0.250	0.0035	0.6557	0.0101	0.6791	0.0151	0.7537	0.0190	0.8332
AM − 3	0.005	0.230	0.018	0.230	0.0035	0.6557	0.0097	0.6791	0.0144	0.7537	0.0180	0.8332
AM − 4	0.005	0.230	0.019	0.230	0.0035	0.6557	0.0097	0.6791	0.0144	0.7537	0.0190	0.8332
BM − 1	0.006	0.250	0.023	0.250	0.0042	0.6557	0.0122	0.6791	0.0183	0.7537	0.0230	0.8332
BM − 2	0.006	0.230	0.020	0.230	0.0042	0.6557	0.0109	0.6791	0.0161	0.7537	0.0200	0.8332
BM − 3	0.006	0.270	0.020	0.270	0.0042	0.6557	0.0109	0.6791	0.0161	0.7537	0.0200	0.8332
BM − 4	0.006	0.270	0.026	0.270	0.0042	0.6557	0.0135	0.6791	0.0206	0.7537	0.0260	0.8332
CM − 1	0.005	0.200	0.020	0.200	0.0035	0.6557	0.0105	0.6791	0.0159	0.7537	0.0200	0.8332
CM − 2	0.005	0.190	0.018	0.190	0.0035	0.6557	0.0097	0.6791	0.0144	0.7537	0.0180	0.8332
CM − 3	0.005	0.180	0.018	0.180	0.0035	0.6557	0.0097	0.6791	0.0144	0.7537	0.0180	0.8332
MRCF − 1	0.008	0.280	0.050	0.280	0.0056	0.6557	0.0245	0.6791	0.0389	0.7537	0.0500	0.8332
MRCF − 2	0.024	0.850	0.120	0.850	0.0168	0.6557	0.0607	0.6791	0.0942	0.7537	0.1200	0.8332
MRCF − 3	0.009	0.450	0.055	0.450	0.0063	0.6557	0.0270	0.6791	0.0428	0.7537	0.0550	0.8332
MRCF − 4	0.010	0.520	0.100	0.520	0.0070	0.6557	0.0465	0.6791	0.0768	0.7537	0.1000	0.8332
SWC − 1	0.010	0.260	0.047	0.260	0.0070	0.6557	0.0244	0.6791	0.0378	0.7537	0.0470	0.8332
SWC − 2	0.010	0.260	0.048	0.260	0.0070	0.6557	0.0244	0.6791	0.0378	0.7537	0.0480	0.8332
MRSF − 1	0.009	0.450	0.055	0.450	0.0063	0.6557	0.0270	0.6791	0.0428	0.7537	0.0550	0.8332
MRSF − 2	0.010	0.520	0.100	0.520	0.0070	0.6557	0.0465	0.6791	0.0768	0.7537	0.1000	0.8332
MRSF − 3	0.010	0.260	0.048	0.260	0.0070	0.6557	0.0244	0.6791	0.0378	0.7537	0.0480	0.8332
LMF − 1	0.004	0.150	0.014	0.150	0.0025	0.6557	0.0075	0.6791	0.0110	0.7537	0.0144	0.8332
LBTF − 1	0.012	0.500	0.050	0.500	0.0091	0.6557	0.0307	0.6791	0.0473	0.7537	0.0500	0.8332
LBTF − 2	0.012	0.500	0.055	0.500	0.0091	0.6557	0.0307	0.6791	0.0473	0.7537	0.0550	0.8332
LBTF − 3	0.013	0.500	0.060	0.500	0.0091	0.6557	0.0307	0.6791	0.0473	0.7537	0.0600	0.8332
LBTF − 4	0.013	0.500	0.062	0.500	0.0091	0.6557	0.0307	0.6791	0.0473	0.7537	0.0620	0.8332



(a) Capacity curve (b) Fragility Curves

Fig. 6. Seismic vulnerability model for building class RCF1.1 L. (a) Capacity curve. (b) Fragility Curves.

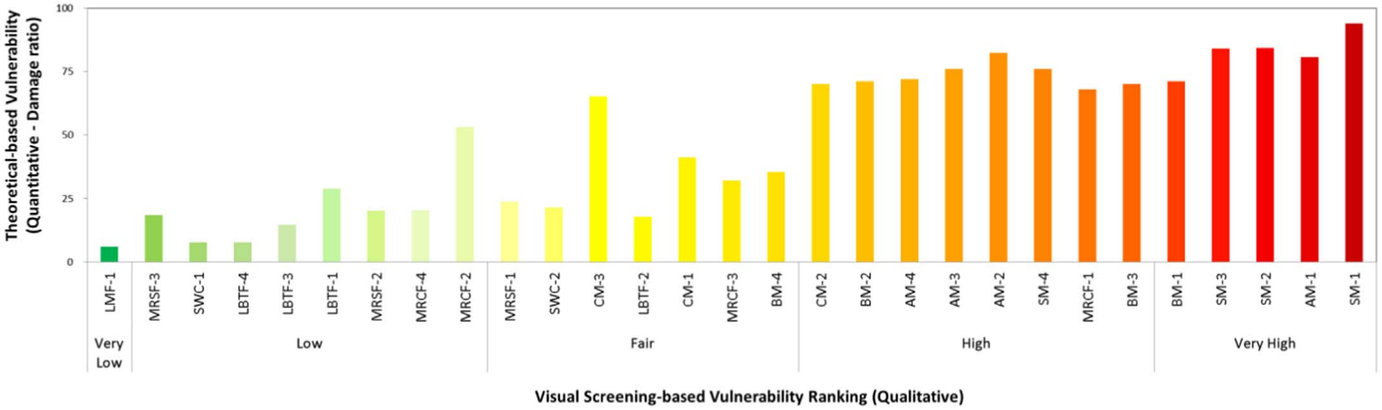


Fig. 7. Comparison of visual screening-based with theoretical-based vulnerability estimations for the existing building stock in the study's test bed region of Central and South Asia.

- Safe physical planning: Building vulnerability is one of the governing factors for rural and urban physical planning. The classification will form the basis for understanding the built environment's vulnerability and develop the strategy for planning and policies. In practice, the proposed building classification has been considered for rural and urban planning in the pilot study areas of Khorog city and some village clusters in Tajikistan.

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The authors acknowledge the sincere professional support of Aga Khan Planning & Building Services (AKPBS), India and Pakistan, Aga Khan Foundation (AKF), Afghanistan and Tajikistan for collecting the facility data from south and central Asia in record timeline from 2012-2013. The authors further express gratitude to Disaster Risk Management Initiative (DRMI) programme of AKDN for providing exceptional management and leadership support to collect the data and conduct rigorous analysis to evolve the stated building typologies as well as to the Norwegian Ministry of Foreign Affairs for funding of Project QRS-10/009 "Earthquake hazard and risk in Kyrgyzstan and Tajikistan with cooperation to Afghanistan and Uzbekistan". The comments and suggestions of receiving editor James LaFave and two anonymous reviewers significantly improved the present manuscript.

Appendix 1. AKDN Rapid Visual Survey Process (Level 1 Survey)

Background

Between April 2012 and December 2013, a "Level 1 Rapid Visual Survey" was conducted of all facilities owned or operated by the AKDN in Central and South Asia. A total of more than 5400 structures were surveyed by national AKDN survey teams, which completed their field surveys using the "Level 0 Pre-Survey" facility data. In compliance to the AKDN safety guidelines, the facility database was updated in 2014, which counted a total of 5554 structures located across the region.

Methodology

The Level 1 Rapid Visual Survey method is based upon widely-respected industry practices for screening structural and non-structural vulnerability of all common building types, notably ATC-13 [1], FEMA 154 [9], NORSAR [20], and EMS-98 [12]. AKDN buildings are categorized using the EMS-98 structural classifications (masonry, reinforced concrete, steel and timber) with sub-class additions to reflect building types unique to Central and South Asia. This expanded version of EMS-98 provides a probable range of seismic vulnerability for each class and sub-class of AKDN structures, i.e. a prediction of how each class is likely to perform under various earthquake intensities. The Level 1 Rapid Visual Survey methodology is illustrated in more detail by Fig. A1.

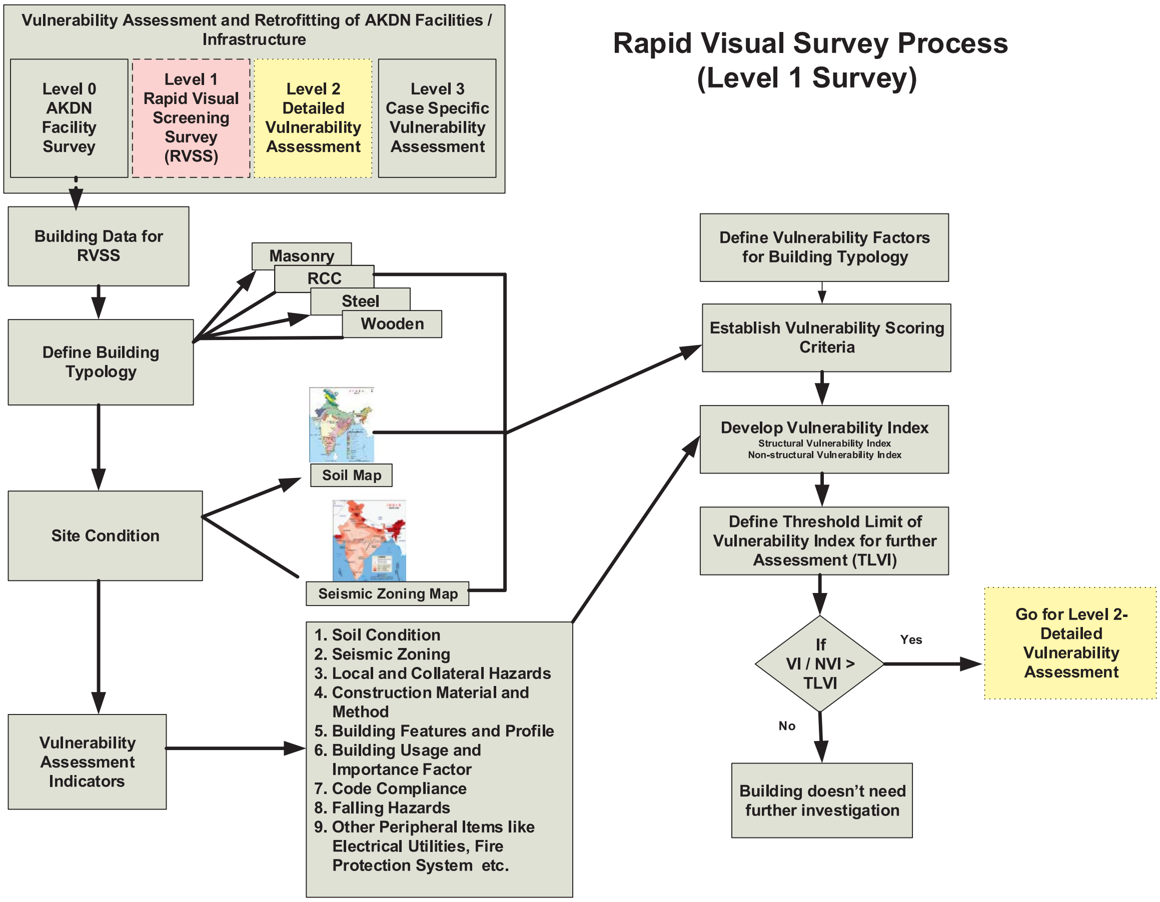

Fig. A1. Flowchart of the AKDN Rapid Visual Survey Process (Level 1 Survey).

Survey process

The AKDN Level 1 Rapid Visual Survey was limited to those facilities owned or operated (leased or under easement) by AKDN agencies in the priority countries. The survey was conducted by a dozen surveyor teams recruited by lead agencies in each country, trained by the Disaster Risk Management Initiative (DRMI) Coordination Office and supervised by national survey managers. Each field survey team was composed of one structural and one non-structural safety specialist, in addition to a driver/logistician.

To enable real-time monitoring and data security, the surveyors were required to use handheld mobile tablet computers preloaded with a custom-built Android-based software, designed to synchronize with the AKDN facility database in Geneva. The software allowed the teams to download and validate Level 0 Pre-Survey data, and then add and upload "integrity-tested" Level 1 survey data to Geneva, securely and without any paper records or manual data entry. The DRMI Coordination Office monitored the process remotely and, in case of concerns with respect tp data quality or rate of progress, provided necessary assistance to the national survey teams. When the survey teams had inadequate internet access in the field, they were authorized to batch their data submissions upon return from each leg of their survey.

The Level 1 surveys required an average of 45 min per facility. (Note: Each AKDN facility includes one or more structures.) The survey teams were required to assess every structure at any facility according to a standard panel of structural and non-structural vulnerability indicators. In addition, the teams captured a series of photographs and drew a building floor plan of each structure. Upon completion of the field surveys, the DRMI Coordination Office completed a formal process of quality assurance and, upon acceptance testing, began to analyze the structural vulnerability of the country datasets. This process was followed by a probabilistic risk estimation of structural and non-structural damage, casualties, functional losses and displacement costs associated with a major earthquake, based upon the HAZUS methodology [4,10]. The findings of this analysis were then reported to each AKDN agency in December 2013, using a custom-built report generation software.

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