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A review of current construction guidelines to inform the design of rammed earth houses in seismically active zones

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ABSTRACT

Sustainability in the materials we use for construction is a prime concern, focusing on reducing the embodied energy and carbon footprints of the materials used. The cement used in concrete products is responsible for a significant proportion of Man's CO_2 emissions and its production requires substantial energy input, as do fired clay products. For this reason, products formed from unfired earthen materials are of increasing interest and the current challenges include devising means of robust design for strength and to address durability concerns. One form of earthen construction that employs an in-situ method is rammed earth, and it is a technique experiencing a revival in various parts of the world. This revival has been partially supported by the development of guides and some standards although there is very little information as compared to traditional building materials. The objective of this paper is to provide a summary of the current guidelines found worldwide, specifically looking at rammed earth construction with seismic provisions and to propose a unified set of guidelines, demonstrated on a case study design.

1. Introduction

Various sources have estimated that building with earth began between approximately 10,000 years ago [1–3], by early agricultural societies [4]. Various earthen building techniques were used across the ancient world, including Europe, China, Africa and the Middle East and the Americas [5]. Early guidelines for earthen building have been found in ancient Egypt with building techniques written or painted on documents around 1500 BC [6]. In Europe during the 14th and 15th century, Saxony, Prussia, and Austria developed their own earthen building codes [7]. Earthen construction experienced a revival in France and Germany after the First and Second World Wars due to a lack of building materials [8] which led to early iterations of building codes and standards. Towards the end of the twentieth century, some countries started to develop earth building codes and standards which incorporated modern structural engineering design aspects. With the onset of man-made climate change, earthen ~~building~~ construction methods are being revisited as a possible means to construct buildings in an eco-friendlier manner but the development of building codes and standards is lacking when compared to more established methods such as steel and concrete.

As previously mentioned, rammed earth construction is one such method of earthen construction which consists of compacting layers of moist earth inside removeable formwork [9]. These layers build up to form the walls of the building under construction as illustrated in Fig. 1.

Up to one third to half the people on earth live in earthen buildings with rammed earth being the most common out of

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approximately 20 other earthen construction techniques, [1,10]. Fig. 2 is based on a similar map by Refs. [9–11], which shows the regions in the world where earthen construction is most prominent. Also shown are the areas subject to seismic activity which can be seen to overlap many of the areas where earthen construction is present. Many of these regions are in developing or low-income countries.

In developed countries, much of the motivation for utilising earthen construction, including rammed earth, is to promote sustainable forms of construction as part of the response to climate change, [12]. However, in countries such as the U.K., there is a reluctance to apply scientific rigour to understanding the properties of earthen materials, which in turn means construction companies tend not to favour earthen buildings for mass construction projects and instead are utilised in bespoke house builds. While in developing countries, earthen construction (including rammed earth) is more common due to the low cost of the material used. Augarde [13], states that applying rigorous scientific analysis to earthen construction will improve the understanding of the material, which in turn will lead to more earthen construction projects which in turn will lead to the development of detailed building codes and standards.

Hall et al. [12], state that many traditional earthen building methods have fallen behind more modern construction methods due to the fact they cannot fulfil basic structural requirements such as being load bearing. This ties back into the point by Augarde [13], and highlights the need for continued research to be carried out so that rammed earth can be fully understood as a construction material in terms of properties and capabilities. Also, with so much rammed earth construction taking place in seismically active regions, clear design specifications for those building in these countries are essential in order to better protect the building's inhabitants.

2. Methodology for this study

The aim of this paper is to undertake literature review in order to determine the current state-of-the-art construction guidelines with regards to rammed earth buildings in seismically active zones. Through this review, any similarities, discrepancies and omissions of critical information relating to seismic design between the various publications will be addressed. Once specific building specifications have been identified from each publication, a new unified set of specifications will be proposed that can be used to build rammed earth buildings in seismically active zones throughout the world.

2.1. Identification of relevant construction guidelines

Firstly, all publications relating to the construction of rammed earth buildings in seismically active zones were identified. The different types of publications included~~,~~ standards, building codes and normative documents.

A standard is a set of technical guidelines that specifies minimum parameters or instructions in the construction process that should be followed. A building code is a standard that has been enacted into law so that those in the construction industry are legally bound to comply with code, [14]. In some cases, the standards can be referenced by the specific building code and therefore become part of the legally enacted building code.

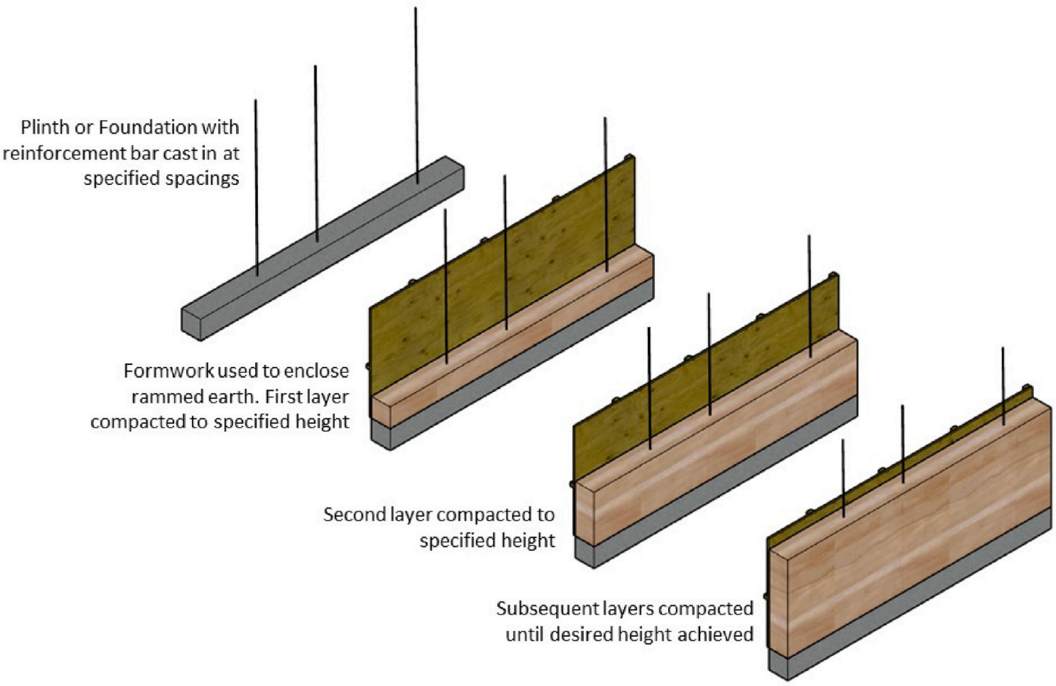

Fig. 1. Rammed earth construction process.

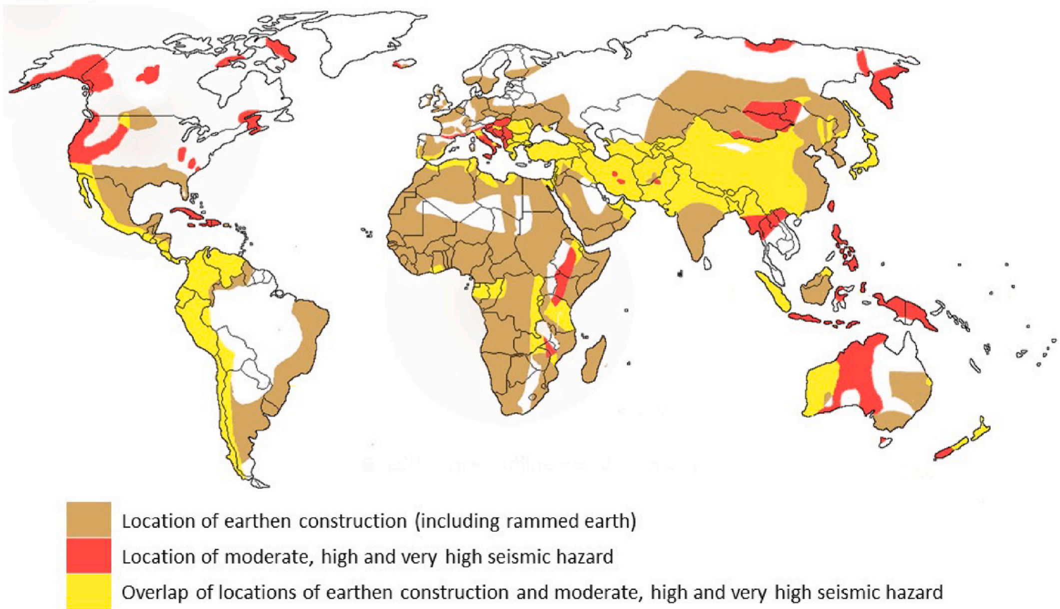

Fig. 2. Locations of earthen construction and seismic hazards [9–11].

Normative documents are publications that are not legal building codes or standards but have been used to inform the specific construction processes. These documents provide instructional guidelines for the construction systems and are not legal acts or standards (including candidate standards). They are generally developed by national technical groups, academia, or non-government organisations in order to develop a new standard [7], or as part of charity work looking to educate those in developing countries in safe construction practices, especially those who participate in self-construction house projects [15]. These include practical manuals, books and technical reports.

Schroder [7], produced a review detailing the various earthen building codes, standards and normative documents, identifying

Table 1
List of rammed earth normative documents, standards and building codes [6].

- ND – Normative document
- S – Standard
- BC – Building Code

No.	Country	Document ID	Type	Ref
1	Afghanistan	Guidelines for Earthquake Resistant Design, Construction and Retrofitting of Buildings in Afghanistan	ND	[36]
2	Africa	Rammed Earth Structures – Code of Practice. THC 03	S	[37]
3	Australia	CSIRO Bulletin 5, 4th ed. (1995)	ND	[18]
4	Australia	HB 195-2002	ND	[8]
5	Australia	EBAA (2004)	ND	[21]
6	Brazil	NBR 13553 (1996)	S	[22]
7	France	Guidelines for earthquake resistant non-engineered construction	ND	[38]
8	Colombia	AIS 610-EP-17	S	[33]
9	Germany	Lehmbau Regeln (2009)	S	[23]
10	Germany	Construction manual for earthquake resistant houses built of earth	ND	[2]
11	India	IS: 2110 (1998)	S	[24]
12	India	IS: 13827 (1998)	S	[39]
13	Kyrgyzstan	PCH-2-87 (1988)	S	[34]
14	Nepal	NBC 204:1994	BC	[40]
15	New Zealand	NZS 4297:1998	S	[41]
16	New Zealand	NZS 4298:1998	S	[42]
17	New Zealand	NZS 4299:1998	S	[43]
18	Nigeria	NBC 10.23 (2006)	BC	[25]
19	Spain	MOPT Tapial (1992)	ND	[26]
20	Switzerland	Regeln zum Bauen mit Lehm (1994)	ND	[27]
21	UK	A Review of Rammed Earth Construction, Innovation Project 'Developing Rammed Earth for UK Housing	ND	[28]
22	UK	Rammed Earth: Design and Construction Guidelines	ND	[19]
23	USA	1997 Uniform Administrative Code Amendment for Earthen Materials and Straw Bale Structures	BC	[20]
24	USA	14.7.4 NMAC (2006)	BC	[44]
25	USA	ASTM E2392/E2392 M (2010)	S	[45]

thirty-three publications from nineteen countries. This list of publications was first refined and amended to show only those specifically addressing rammed earth construction, as shown in Table 1, and refined again to show those including seismic provisions highlighted, as shown in Table 2. Table 2 shows 13 publications, a number of which are based on Arya et al. (2014) – Guidelines for Earthquake Resistant Non-Engineered Construction [16].

In many cases the publications identified, cover a number of earthen construction techniques including adobe, compressed earth block, cob, poured earth, wattle and daub and rammed earth. While many of the publications make specific mention of rammed earth, much of the detail presented in terms of construction details and requirements apply to all types of earthen construction unless otherwise specified. These vary quite significantly in several areas including but not limited to number of topics covered, level of technical detail, length, legal status, intended reader.

Omitted publications from Table 2 include normative documents, standards and building codes [17–28]. These still provide informative guidelines and specifications for rammed earth construction but lack seismic provisions. Other publications, which were not included in Table 1 or 2, which discuss building with rammed earth in seismic zones, but without including any building specifications include Keable and Keable [29], Peace Corps [30], Krahn [31] and Easton [5]. 'Manual para la rehabilitacion de viviendas construidas en adobe y tapia pisada' ('Manual for the rehabilitation of houses built in adobe and rammed earth' published by Asociacion Colombia de Ingenieria Seismica (Colombian Association of Seismic Engineering) [32] and 'Evaluation and Intervention of Heritage Buildings of one and two Adobe Floor and Rammed Earth', published by Ministry of Housing, City and Territory of the Government of Colombia in 2019 [33], are examples of publications which address rammed earth in seismic zones but from a restoration or repair standpoint. While important information is presented, this review will focus only on the construction of new rammed earth buildings only. Kyrgyzstan's standard, PCH-2-87 (1988) [34] is also not included due to difficulties in obtaining a copy.

2.2. Producing universal design for rammed earth building in seismically active zones

The Department of Urban Development and Building Construction under the auspices of the Nepalese Government produced a design catalogue for the reconstruction of earthquake resistant houses following the 2015 earthquakes which resulted in approximately 8150 deaths [35]. This document was produced to provide clear guidance for rural households, regarding earthquake resistant construction techniques. This is a very useful document as it provides clear information for people who wish build various sized homes that can better withstand seismic forces. While a number of building techniques were covered by these publications, rammed earth was not addressed. This paper now attempts to fill this gap. By identifying the relevant documents shown in Table 2, building specifications relating to construction in seismically active zones were tabulated in order to identify any similarities or differences between publications. These differences will then be reviewed and used to inform a universal set of specifications which would satisfy all publications listed in Table 2.

3. Review of rammed earth standards, building codes and normative documents with seismic design provisions

3.1. Background information

The following publications detailing construction guidelines for building with rammed earth in seismic zones are briefly summarised below.

3.1.1. Arya, 2003 - guidelines for earthquake resistant design, construction and retrofitting of buildings in Afghanistan

This normative document [36] was prepared by the Ministry of Urban Development and Housing by the Government of Afghanistan and the United Nations Centre for Regional Development, with contributions from Professor Anand S. Arya. It covers background information on building materials and construction in Afghanistan, damage caused by earthquakes, explanations of seismic zoning and general earthquake resistant design with a separate section on repair, restoration and seismic retrofitting of masonry buildings. It also addresses earthquake resistant design of specific building types, including earthen construction, with details on

Table 2
List of rammed earth normative documents, standards and building codes with seismic provisions [6].

- ND – Normative document
- S – Standard
- BC – Building Code

No.	Country	Document ID	Type	Ref
1	Afghanistan	Guidelines for Earthquake Resistant Design, Construction and Retrofitting of Buildings in Afghanistan	ND	[36]
2	Australia	HB 195-2002	ND	[8]
3	Colombia	AIS 610-EP-17	S	[33]
4	France	Guidelines for earthquake resistant non-engineered construction	ND	[38]
5	Germany	Construction manual for earthquake resistant houses built of earth	ND	[2]
6	India	IS: 13827 (1998)	S	[39]
7	Kyrgyzstan	PCH-2-87 (1988)	S	[34]
8	Nepal	NBC 204:1994	BC	[40]
9	New Zealand	NZS 4297:1998	S	[41]
10	New Zealand	NZS 4298:1998	S	[42]
11	New Zealand	NZS 4299:1998	S	[43]
12	USA	14.7.4 NMAC (2006)	BC	[44]
13	USA	ASTM E2392/E2392 M (2010)	S	[45]

hand-formed layered walls (e.g. pasksha walling), adobe (e.g. khiste Kham) and rammed earth. It briefly describes the process involved in creating a rammed earth wall with subsequent information on wall dimensions, openings and general building configuration being addressed without specifying a particular method of earthen construction.

3.1.2. Arya et al., 2014 – Guidelines for Earthquake Resistant Non-engineered construction

This normative document [16] is the revised version of the first official guideline solely focusing on non-engineered construction entitled "Basic Concepts, Part 2: Non-engineered Construction by Arya et al. [46], This was further revised into "Guidelines for Earthquake Resistant Non-Engineered Construction" by Arya et al. [38], and slightly revised in 2014 to its current version [16]. It covers other construction and repair methods for masonry, stone, wooden, non-engineered reinforced concrete, and earthen buildings. The content relating to earthen buildings is similar to that presented in the Indian Standard, IS: 13837:1998 [39] and Arya, [36].

3.1.3. Standards Australia - HB 195-2002

This normative document [8] was prepared by Professor Peter Walker of Bath University, UK and Standards Australia. Originally Australia and New Zealand has planned to develop a joint standard for earthen construction to cover compressed earth block, rammed earth, poured earth, cob and mud brick however this idea was abandoned. Standards Australia then decided to publish this handbook instead in 2002. Even though it was published by Standards Australia it has not been published under the auspices of the Standards Australia Committee, [7]. However due to the high-quality level of information provided, it has been included in this paper for comparison with other publications. Earthen building construction details are addressed for the various earthen construction techniques, including rammed earth with a brief section addressing design criteria for earthquakes.

3.1.4. Minke, 2001 - construction manual for earthquake resistant houses built of earth

This normative document [2] was authored by Gernot Minke in 2001, based upon work by the University of Kassel, Germany and the German organisations DFG and GTZ Gmbh. The information provided is partly derived from former research projects the author was involved and was originally published in Spanish and focused on rural housing in the Andes mountains in South America. It focuses on the construction of low-cost single storey earthen houses which are subject to seismic activity. Various earthen building techniques are addressed including adobe, wattle and daub and rammed earth. In relation to rammed earth, details are given on the stabilisation of the material through mass and shape as well as details on recommended internal reinforcement techniques. Additional information relating to critical joints between building elements, gables, roofs and wall openings are also provided.

3.1.5. Bureau of Indian Standards - IS: 13837 (1998)

This standard [39] was developed by the Bureau of Indian Standards and contains much the same information present in Arya et al. [36], as one of the key contributors to both documents was Professor Anand S. Arya. It covers the design and construction of earthen structures including adobe, rammed earth, cob and assam (wattle and daub). to resist earthquakes without the use of stabilisers. The main topics covered include tests to determine suitability of soil, details on block size for adobe and sundried blocks, general overview of rammed earth construction and wood frame details for adobe in mud mortar. Recommendations for building in seismic areas are given but do not specifically mention rammed earth but can be generally be applied where applicable.

3.1.6. Nepal bureau of Standards and metrology - NBC 204:1994

This standard [40] was developed by the Government of Nepal's Department of Urban Development and Building Construction and covers guidelines which are aimed at improving the seismic resistance of earthen buildings including mud walls, adobe and rammed earth. It addresses considerations for materials to be used, site selection, and technical information on foundations, walls, floors and roofs and details on utilising seismic resistant components such as internal reinforcement, horizontal bands and other bracing techniques. The details given here are applied with no specific differentiation between the types of earthen construction.

3.1.7. Standards New Zealand - standards for earthen construction

The New Zealand standards for earthen construction were developed for the standards council of New Zealand and comprise of three separate standards which are listed below:

- NZS 4297:1998 - Engineering Design of Earth Buildings [41],
- NZS 4298:1998 - Materials and Workmanship for earth buildings, 1998 [42],
- NZS 4299:1998 - Earth Buildings not requiring specific design, 1998 (including amendment #1, December 1999) [43],

They cover information on the design and construction methods of earthen buildings and are summarised individually in the next section.

3.1.7.1. NZS 4297:1998 - Engineering Design of Earth Buildings. This standard [41] investigates the structural aspects used in the design of earthen buildings. It follows the principles similar to that of reinforced and unreinforced masonry and reinforced concrete. Limit state design principles are used similar to other material design standards with earthquake loads analysed using methods of assessment for unreinforced masonry buildings.

3.1.7.2. NZS 4298:1998 - Materials and Workmanship for earth buildings. This standard [42] sets out the specific material and workmanship requirements of earthen construction of single and two storey earthen buildings in terms of material testing requirements, working in different weather conditions, finishes and descriptive sections on reinforcement details for the various types of earthen construction methods. Rammed earth is addressed in its own section detailing information on moisture content, compaction, construction joints, cracks and building finishes.

3.1.7.3. NZS 4299:1998 - earth buildings not requiring specific design, (including amendment #1, December 1999). This standard [43] takes the information discussed in NZS 4297:1998 [41] and NZS 4298:1998 [42] and incorporates it into detailed structural specifications. This includes details on site requirements, types of soil, additives, soil compaction, footings, walls, structural diaphragms, bond beams, lintels, wall openings and control joints. Again, all types of earthen construction methods are discussed with particular focus on earth brick which is understandable as the codes use the same principles as the masonry codes. Detailed drawings of reinforcement layouts for bracing walls for both horizontal and vertical reinforcement are included as well as specific material properties such as compressive strength, shear strength which are to be used in the design of a standard grade earthen wall.

3.1.8. Construction Industries Division of the Regulation and Licensing Department, new Mexico, USA - 14.7.4 NMAC (2006)

This standard [44], was issued in 2016 by Construction Industries Division of the Regulation and Licensing Department and aims to establish minimum standards for all types of earthen building in the state of New Mexico, USA. It focuses mainly on adobe, rammed earth and compressed earth blocks. Guidance on building height, thickness of walls, openings in walls and general foundation details are provided. Descriptive sections on rammed earth soil specifications cover compressive strength requirements, use of stabilised and unstabilised soil, compaction methods, curing, attaching loadbearing wood or steel, doors, windows, insulation, bond beams are included.

3.1.9. ASTM E2392-05, Standard guide for design of earthen wall building systems, 2005, (USA)

This standard [45] was developed by ASTM International and covers adobe, compressed block, rammed earth, cob, and poured earth walls and references various other standards including ASCE 7 [48] and New Zealand Standards [41–43] in its recommendations and specifications. It also focuses on the principles of sustainability as well as the technical issues associated with Earthen Building in general and is to be used as a guide in the development of standards and buildings codes for earthen building systems. Technical issues discussed include materials to be used in earthen construction, manufacturing process, operational performance, indoor environmental quality, structural engineering design, stabilisation and design criteria in terms of seismic design. It also includes some non-mandatory information in its appendix covering empirical design and minimum detailing requirements for earthen structures.

3.2. Detailed technical review of publications

3.2.1. Building configuration

Building configuration relates to the building's size and shape and therefore determines how seismic forces are distributed within the structure. General recommendations for building in seismic zones state that buildings should be regular in shape with low height to base ratios and be symmetrical as possible. The shape specified for rammed earthen buildings is addressed in six [2,8,36,39,40,45] publications and for five of these the specifications simply states that the buildings should be symmetrical as possible. NBC 204:1994 [40] differs by specifying that the breath to length ratio of the building shall not exceed 1:3. This ratio also applies internal rooms or areas within the building. A maximum storey is mentioned in all publications except Minke [2]. The publications [8,39,40,45] specify a maximum of one storey with the remaining publications specifying a maximum of two storeys. Arya [36], specifications alter between one and two storeys depending on the location's seismic code classification. These specifications are relatively consistent in each publication with no major outlier and adhere to the general recommendations that building configuration should be as regular as possible.

3.2.2. Foundations

Foundation specifications are addressed in six of the publications [2,8,36,39,40,43]. The width of the strip footings in mentioned in four publications [2,36,40,43] with Arya [36], and Minke [2], specifying varying widths depending on the soil type and specific seismic zone classification of the location of the building. These widths vary from specified values of between 0.5 m and 0.7 m or in the case of NBC 204:1994 [40], not less than the wall thickness plus 0.3 m. The depth of the foundation is addressed in four publications with values ranging from a minimum of 0.3 m–0.6 m.

While some of the publications do not give specifications on foundations for rammed earth buildings, there are other codes and standards available in most countries which address foundation design. Therefore, is recommended that additional codes for elements like foundations be read in conjunction with the publications listed in this study.

3.2.3. Wall dimensions

Wall dimension specifications are addressed across various factors in the publications, including thickness, length, height, and buttress spacing. In terms of minimum thickness, values are given in seven publications [2,8,36,39–41,44], with values ranging from 0.2 m to 0.457 m. Minke [2] specifies the minimum thickness as not less than the height of the building divided by eight. The variance here is quite high e.g., more than double the recommended thickness between Standards Australia [8], and NMAC 14-7-4:2016 [44] with NBC 204:1994 [40], also having higher minimum values.

Two types of wall lengths are addressed, supported and unsupported. The maximum length of unsupported walls is mentioned in two publications with Standards Australia [8], and NBC 204:1994 [40], deriving the value as a factor of the wall thickness, e.g. 15 times the thickness and 10 times the thickness respectively. This give a 33% difference in recommended lengths of unsupported walls which is quite high, especially over larger distances.

For supported walls, specifications are given in three publications [36,39,41] with both Arya [36] and IS13837 [39] giving the same recommendation of not greater than 10 times the thickness. NZS 4297:1998 [41] specifies a value of 12 m depending on the length of the connected bracing wall. These values give a wide range of lengths for supported walls. For example, assuming the thickness for both Arya [36] and IS13837:1993 [39] is 0.3 m as specified in the standard, the maximum length of the unsupported wall will be 3 m. This is obviously significantly lower than the 12 m specified in NZS 4297:1998 [41]. Supports for walls can be either bracing walls or buttresses. Buttress spacing is addressed in two publications with both IS13837:1993 [39] and NBC 204:1994 [40] specifying a distance 10 times the wall thickness which corresponds to the supported wall length.

The maximum height of the walls is addressed in eight publications [2,8,39–41,43–45] with five publications [2,8,39,40,45], stating the height should be a factor of the wall thickness. NZS 4297:1998 [41] and NZS 4299:1998 [43] specifications vary depending on the seismic zone classification of the location of the building and NMAC 14.7.4:2016 [44] specifies a height range of 3–3.6 m.

3.2.4. Opening in walls

Specifications on the openings, such as windows and doors, in the walls of rammed earth buildings are mentioned in a number of publications under different headings. The maximum percentage of a wall an opening can occupy is given in five publications [2,8,36,39,45], ranging from 1/5 to 1/3 the total wall area. Arya [36] and IS13837:1993 [39] give varying specifications depending on the specific seismic zone classification of the area where the building in being constructed.

The maximum opening size is mentioned in five publications [2,36,39,40,45], and all have a consistent recommendation of 1.2 m.

The minimum distance from the corner of the building to the opening is mentioned in six publications [2,8,36,39,40,44], with values ranging from 0.75 m to 1.2 m. Minke [2] deviates from giving a specific distance and instead recommends the minimum distance as being not less than 1/3 the height of the wall or not less than 1 m.

The bearing length of lintels above openings is mentioned in six publications [2,8,36,39,44,45], with five publications specifying a length of not less than 0.3 m or 0.4 m. The only outlier is the value for NMAC 14.7.4:2016 [44] which gives a value of 0.05 m which is significantly lower than other recommendations. Openings in walls have been shown to have poor seismic capacity and the exact relationship between the size and position of openings and seismic capacity of the building's wall is not clear [49] which may explain some of the conflicting information presented in the various publications.

3.2.5. Horizontal reinforcement

3.2.5.1. Horizontal reinforcement bars. Horizontal reinforcement specifications are mentioned in three publications [8,39,43]. Standards Australia [8] and NZS 4299:1998 [43] both specify the use of 12 mm steel rebar while IS13837:1993 [39] mention the use of horizontal reinforcement but does not specify any details other than stating a mesh of bamboo canes can be used. The spacing between reinforcement varies in that Standards Australia [8] recommends 450 mm centre to centre whereas NZS 4297:1998 [41] recommends 900 mm spacing.

It must be noted that the use of horizontal reinforcement bars can weaken the structure and cause horizontal cracking in the wall which can negatively affect the walls ability to withstand shear forces [2]. Also, there are issues with placing horizontal reinforcement bars in rammed earth, in terms of inspection and compacting [2,50], which may explain why this topic is not specified in more publications.

3.2.5.2. Horizontal bands/ring beams/bond beams. According to the Nepalese code, NBC 202:1994 [51], reinforced concrete bands, positioned continuously across both load-bearing longitudinal and transverse walls, are one of the most effective horizontal reinforcement methods. These horizontal bands help support lateral loads between structural walls which ties them together, resulting in a structure better able to withstand seismic forces. Different publications refer to them as either horizontal bands, ring beams or bond beams.

All publications mention the use of horizontal bands with some giving specific details in terms of dimensions, material type, internal reinforcement details. Timber and concrete beams are specified in a number of publications with NBC 204:1994 [40] recommending concrete bands but acknowledging that these may not be possible due to cost and supply constraints for people in rural areas. It recommends that bamboo or timber should be used as alternatives and provides diagrams on how timber or bamboo bands would be placed with details on how to fix these to the wall.

NZS 4297:1998 [41], specifies dimensions for timber and concrete bands which vary depending on the earthquake zone factor, number of storeys or whether the band is to act as a structural diaphragm. Reinforcement details for the concrete bands also vary for the same reasons.

ASTM E2392-M10:2010 [45] only mentions the use of concrete bands but states that they should be able to hold the weight of one man (i.e. 100 kg) and mentions the need for reinforcement in the band without specifying any details.

An overview of all the publications show that when recommended dimensions are provided for both timber and concrete, they are all relatively close with no major outliers.

3.2.5.3. Plinth beam. The use of a plinth beam is specified in Refs. [2,8,36,39,40,45]. Plinth beams are generally used to spread the load of the wall evenly over the foundation but in rammed earth construction they are also recommended to help protect the base of the walls against floods/water damage. Minke [2], Arya [35], and IS13837:1993 [38], specify a minimum height above ground of 300 mm with the other publications mentioning using a plinth beam without specifying any details.

3.2.6. Vertical reinforcement

Vertical reinforcement is an essential element of a rammed earth building's ability to withstand seismic forces. Reinforcement is cast into foundations and can then be connected into plinth beams and run up through the wall into the horizontal bands which can improve the buildings ability to withstand the horizontal forces associated with earthquakes. The vertical reinforcement also enables the walls to resist the tensile forces experienced during an earthquake which may cause un-bonding from the foundation [52].

Despite vertical reinforcement being a key element in resisting seismic forces, specifications are only given by two publications and both specify the use of 12 mm steel rebar. As with the horizontal reinforcement, IS13837:1993 [39] mentions the use of vertical reinforcement but does not specify any details other than stating a mesh of bamboo canes can be used. The spacing between the rebar

Table 3
Summary of specified material properties for rammed earth construction.

ID	Arya, (2003)	HB 195-2002	Minke, (2001)	IS 13837:1993	NBC 204:1994	NZS 4297:1998	NZS 4298:1998	NZS 4299:1998	NMAC 14-7-4:2016	ASTM E2392-M10
Reference #	[36]	[8]	[2]	[39]	[40]	[41]	[42]	[43]	[44]	[45]
Compressive strength (N/mm^2)	–	0.4–0.6[fc]	–	–	–	0.5	–	–	2.07	n.s.
Bending strength (N/mm^2)	–	0.5–2.0[fc] or 0.0’[a]	–	–	–	0.1	–	–	–	–
Moisture content (%)	–	–	–	–	–	–	–	–	–	n.s
Dry Density (kg/m^3)	–	1700–2000	–	–	–	–	–	–	–	n.s
Young’s Modulus (N/mm^2)	–	500	–	–	–	300 * compressive strength	–	–	–	–
Shear strength (N/mm^2)	–	0′[1]	–	–	–	0.0–0.08	–	–	–	–

n.s. = mentioned but not specified.
- = not mentioned.
fc = Design value for characteristic compressive strength.
[a] Taken as 0 unless tested.

again varies between publications with Standards Australia [8], specifying 1–1.5 m centre to centre and NZS 4297:1998 [41] specifying different values depending on the height of the building and depending on whether horizontal reinforcement is used.

Despite the important role vertical reinforcement plays in helping rammed earth withstand seismic forces, Lindsay [53] states that the use of vertical reinforcement should not be used in stabilised rammed earth as the material can shrink on the vertical plane which can lead to cracking. There are also issues with obstruction of the rammer, associated with the compaction of rammed earth when using vertical reinforcement.

A solution to these issues is given by Minke [2], who states that when rammed earth with vertical reinforcement has shrank after drying, the gap which is usually between the roof structure and or plinth beam, can be filled with earth. These joints can then rupture during an earthquake and allow independent movement of each element which then absorbs some of the seismic energy. The joints can then be refilled afterwards during repair works.

3.2.7. Roof details

Roof details are mentioned in seven publications [2,8,39–41,43,44] with all of these stating that the roof should be as light as possible and recommend timber or bamboo as the material to be used. They also state that the roof should be securely fixed to the walls or horizontal band. Roof dimensions, in terms of height and pitch, are mentioned in four publications [2,8,40,43] but only NZS 4299:1998 [43] provides dimensions for height and pitch but these vary depending on roof type (i.e. hip roof, earthen wall gable or timber gable).

Proper roof construction is essential as in the case of timber A-frame trusses which would be used in some gable roofs, which if improperly designed, may transmit horizontal forces into the walls which in turn may lead to leaning or cracking of the wall, thus compromising the structural integrity of the building and therefore its ability to withstand seismic forces [54]. A flexible roof that is supported on top of the walls will act as a box and will be better able to resist lateral loads and improve the buildings ability to withstand the seismic forces [16].

3.2.8. Material properties

The publications in Table 2 also contained some specifications for certain material properties which have been summarised in Table 3. Here minimum or recommended material properties are shown in three publications only, with the Australian Earth Building Handbook [8] providing the most detail. This lack of detail for such an important aspect of rammed earth is concerning. Even if all the structural specifications applied, a rammed earth building will fail if the soil itself does not have adequate material properties. This lack of information is likely due to the varying nature of the soils used in terms of its constituent materials, e.g. clay, sand and aggregate contents which would make reliable values difficult to specify. This is why a lot of published research is focused on obtaining various material properties of rammed earth, with every study using a unique soil mixture to produce test samples. Peric et al. [55] produced a review looking at mechanical properties of unstabilised rammed earth and perhaps minimum values derived from such reviews could be used to inform the material properties specifications in construction guidelines in the future.

3.3. Discussion

3.3.1. Difference in documents

From the detailed review of publications listed in Table 1, it can be seen that there is a wide variety in the level of content and details presented in these publications. Part of this is likely due to the type of publication and target user. Nationally approved building codes or standards in wealthy countries such as New Zealand [41–43] have significantly more construction details than some normative documents, for example Minke [2], which is targeted at users building low cost housing in rural areas in South America. This difference in detail does not negate the normative documents as they are often the result of programmes involving actual construction projects in rural areas in developing countries using local workmanship and experience, in conjunction with research groups from universities or charities. It has also been seen that some building codes lack the level of detail presented in some normative documents and standards. Another key aspect is the varying intensity of earthquakes that occur in different regions around the world. While some areas may be subject to moderate intensity earthquakes, other areas may be subject to higher intensity earthquakes on a much more infrequent basis. This varying intensity may also explain the variance in building specifications identified.

As mentioned in NBC 204:1994 [40], many of the recommended materials for building seismic resistant houses are not available in rural areas of low-income countries which then cause a conflict with specifications given in building codes, standards or normative documents. During the 6th World Conference on Earthquake Engineering, Professor Anand S. Arya stated that separate seismic codes were needed for non-engineered buildings. Non-engineered buildings were described by Arya as:

"those which are spontaneously and informally constructed in various countries in the traditional manner, without any or little intervention by qualified architects and engineers in their design" [56].

Using this definition as a guide, it can be said that many rammed earth houses would be classed as non-engineered because much of the construction of rammed earth buildings in developing countries is undertaken by the owner of the building, particularly in rural areas, due to the low cost and limited training needed for construction, [57]. Schildkamp and Araki [58], discusses a similar situation relating to rubble stone masonry where they state that many of the practical manuals or normative documents relating to the construction of rubble stone masonry buildings are directly targeting the non-engineered user groups as engineers are seldom available in the rural areas of developing countries. For these reasons it is important that further work be carried out to address this conflict relating to developing countries requiring an engineer to be involved in the design of earthquake resistant structures and the fact no engineers are available to do so, even though many non-engineered buildings, including rammed earthen buildings are constructed in seismic zones.

Table 4
Summary of rammed earth construction publications with seismic provisions.

ID	Arya, (2003)	HB 195-2002	Minke, (2001)	IS 13837:1993	NBC 204:1994	NZS 4297:1998	NZS 4298:1998	NZS 4299:1998	NMAC 14-7-4:2016	ASTM E2392-M10
Reference	[36]	[8]	[2]	[39]	[40]	[41]	[42]	[43]	[44]	[45]
Building size/shape										
Building shape	symmetrical	symmetrical	symmetrical	symmetrical	1:3	–	–	–	–	symmetrical
Max Storey	1–2	1		1	1	2	2	2	2	1
Foundations details (m)										
Width of strip footings	Varies [a]		t + 0.2		≥ t +0.3	–	–	0.28–0.45	–	–
Depth	min 0.5	min 0.3		min 0.4	0.6	–	–	150–300	–	–
Wall Dimensions (m)										
Min external wall thickness	0.3	0.2	≥ H/8	0.3	0.4–0.45	0.25–0.35	–	–	0.457	–
Wall length (unsupported)	–	15 t	–	–	10 t	–	–	–	–	–
Wall length (supported)	≤10 t	–	–	≤10 t	–	≥12	–	–	–	–
Height	–	≤10 t	≤8t	≤8 t	2.5 or ≤ 8 t	Varies [a]	–	Varies [a]	3–3.6	6t or 8 t [b]
Buttress spacing (max)	–	–	–	10 t	10 t	–	–	–	–	–
Openings in wall (m)										
Max % of total wall (%)	1/3 - 2/5 [b]	1/3	1/3	1/3 - 1/2 [b]	–	–	–	–	–	1/3
Max opening size	1.2	–	1.2	1.2	1.2		–	–		1.2
Dist. corner to opening (min)	1.2	0.75	≤1/3 H or ≤ 1	1.2	1.2	–	–	–	0.914	–
Bearing length of lintel above op.	≤0.3	0.3	≤0.4	≤0.3	–	–	–	–	0.05	0.3
Horizontal Reinforcement bars (mm)										
Diameter	–	12	–	n.s	–	–	–	12	–	–
Spacing between reinforcement		450 ctc	–	n.s	–	–	–	900	–	–
Vertical Reinforcement bars (mm)										
Diameter	–	12	–	n.s	–	–	–	12	–	–
Spacing between reinforcement	–	1–1.5 ctc	–	n.s	–	–	–	Varies [c]	–	≯ H
Horizontal band/ring beam										
Material: concrete	–	other	n.s	n.s	n.s	–	other	–	–	–
Height	–	100–200	–	–	–	–	–	Varies[b]	–	–
Depth	–	125–300	–	–	–	–	–	Varies[b]	152.4	–
Strength	–	–	–	–	–	–	–	–	17.2 N/mm2	100kg PL
Steel rebar no. & Dia (mm)	–	2⌀12 or 16	–	–	–	–	–	Varies[b]	2 ⌀ 12.7	n.s.
Links dia & ctc	–	10 @ 400	–	–	–	–	–	Varies[b]	–	n.s
Material Wood	timber	–	n.s	timber	bamboo/ timber		other	timber	timber	–
Height	50	–	–	50–70	n.s	–	–	50	n.s.	–
Depth	125	–	–	70–150	n.s	–	–	200	n.s.	–
Plinth beam										
Height above ground (mm)	min 300	n.s.	min 300	min 300	n.s.	–	–	–	–	n.s.
Roof details					lots of detail					
Type	–	timber	timber	timber	timber/ bamboo	n.s	–	timber	n.s	–
Dimensions	–	n.s.	n.s.	–	n.s	–	–	Varies depending on roof type	–	–
Recommended shape	–	–	Pyramid	–	Gable	–	–	Gable	–	–
Eaves overhang (mm)	–	min 400	–	500	–	–	–	600	–	–

t = minimum wall thickness.
W = width of building.
ctc = centre to centre.
H = Height of building.
n.s. = mentioned but not specified.
- = not mentioned.
[a] - Varies depending on soil type and seismic zone classification.
[b] Varies depending on seismic zone classification.
[c] Varies depending on height of building and reinforcement type.

3.3.2. Seismic design

From reviewing the publications on construction guidelines for rammed earth houses in seismically active zone, it is clear than most of these documents are intended as instructional publications, providing building specifications that should be followed. Only Arya [36], and NZS 4297:1998 [41] include formulas for seismic design. Some publications reference other publications for further details on seismic design. For example, NZS 4297:1998 [41] also states that seismic design loads should be in accordance to NZS 4203:1992 [59]. Standards Australia [8] state that design guidelines from NZS 4297:1998 [41] may be used for seismic load design. IS13837:1993 [39] references IS1893 Part 1:2002 [60] for seismic design. ASTM E2392-M10 [45] specifies that seismic design should be carried out in accordance to ASCE 7 [48]. While not specifically mentioned in NBC 204:2015 [40], seismic design is covered the Nepalese code NBC 105:1994(2007) [61] which in turn states that it should be applied in conjunction with the Indian Standard, IS4326:1976 - Code of Practice for Earthquake Resistant Design and Construction of Buildings [62].

This situation means that the reader needs to move between multiple publications in order to carry out a seismic design while following the construction guidelines presented in the publications shown in Table 4, which may lead to information being misinterpreted or overlooked [58]. A possible solution to this situation would be to have a unified code, similar to Eurocode 8, Part 1 - General rules, seismic actions and rules for buildings. In this standard, there are specific rules for steel, concrete and masonry buildings which look at the specific design criteria for the different construction materials, providing detailed information on design calculations in order to ensure that structures are able to withstand seismic forces. This may not be currently possible for rammed earth construction or any earthen construction due to the lack of research into the material properties and structural behaviour of the various earthen materials. This is why most publications are adapted from masonry codes, but the applicability of design methods for earthen construction does not appear to be well researched, therefore the applicability of these masonry codes needs to be studied more.

Table 5
Specifications for earthquake proof rammed earth house.

General	Specifications for Case study	Comment
Building size/shape		
Building ratio	Symmetrical	Most common specification given
Max Storey	1	Most common specification given
Foundations details (m)		
Width of strip footings	0.6	Average of specifications given
Depth	0.5	Average of specifications given
Wall Dimensions (m)		
Min external wall thickness (t)	0.3	Average of wall thicknesses rounded to nearest 0.1
Wall length (unsupported)	3	Taken from NBC 204:1994 from as conservative value
Wall length (supported)	3	Taken from HB195-2002, as this was the only publication with both wall lengths
Height	2.4	Most common spec (8*wall thickness)
Buttress spacing	min 0.3	Taken as 10 * minimum thickness of wall
Openings in wall (m)		
Max % of total wall (%)	1/3	Most common specification given
Max opening size	≤1.2	Most common specification given
Dist. corner to opening (min)	1	Median value of those given
Bearing length of lintel above op.	0.3	Most common specification given
Horizontal Reinforcement bars		
Diameter (mm)	12	Satisfies all given recommendations
Spacing between reinforcement (m)	0.9	Satisfies all given recommendations
Vertical Reinforcement bars (mm)		
Diameter (mm)	12	Satisfies all given recommendations
Spacing between reinforcement (m)	1.5	Satisfies all given recommendations
Horizontal bands/ring beam (mm)		
Material: concrete		
Height	175	Satisfies all given recommendations
Depth	300	Satisfies recommendations from publications and matches wall thickness
Strength	n/a	Quality concrete should be used and compacted correctly
Steel rebar no. & Dia (mm)	2ø12	Satisfies all given recommendations
Links dia & ctc	10 @ 400	Satisfies all given recommendations
Material Wood		
Height minimum (mm)	50	Satisfies all given recommendations
Depth minimum (mm)	200	Satisfies all given recommendations
Plinth beam		
Height above ground (mm)	300	Most common specification given & satisfies all given recommendations
Roof details		
Type	Timber	Satisfies all given recommendations
Dimensions (height, pitch)	Max 3.6 m, 25°	Based on details from NZS4299 (only publication with specific details)
Recommended shape	Gable/Pyramid (Hip)	Most common specification given
Eaves overhang (mm)	600	Satisfies all recommendations

4. Theoretical case study of rammed earth house

4.1. Background information

A potential solution for this predicament could be to have a standard house design that meets the various specifications for building in seismic zones that has been design and analysed and proven to be safe.

The Government of Nepal published the Design Catalogue for Reconstruction of Earthquake Resistant Houses, Volumes I [63] and Volume II [64], in 2015 in the aftermath of the 25th of April and May 12, 2015 earthquakes. The objective of these publications is to give clear guidance to rural households in relation to earthquake resistant construction techniques. Volume I [63] provides plans of model houses for stone masonry in cement mortar, brick masonry in cement mortar, stone masonry in mud mortar and brick masonry in mud mortar and Volume II [64] provides plans for houses using alternate masonry techniques, including but not limited to interlocking brick masonry, bamboo and stone masonry hybrid structure and random rubble masonry with wire containment. Minimum requirements for several different aspects are given including but not limited to site selection, shape of house, wall details, vertical reinforcement, horizontal bands and materials to be used. Floor plans and sections are given for different size buildings with reference to relevant technical details. The designs in the catalogue have all been prepared in compliance with the revised National Building Code for Seismic Design of Buildings of Nepal [61] however there is no provision for rammed earth construction in either volume. Using this design catalogue as a template and the information taken from the publications addressing rammed earth construction with seismic provisions, the author will develop a plan for an earthquake resistant rammed earth house.

4.2. Earthquake resistant rammed earth house

4.2.1. Building specifications for earthquake resistant rammed earth house

The specifications from the publications discussed earlier have been reviewed and shown to vary from one publication to another. This variance in specifications across different publications from different countries and regions indicates that seismic resistance of rammed earth houses needs to be investigated more than is currently the case.

Table 4 provided a summary of the specifications related to building with rammed earth in seismic zones and using this information, a new set of specifications were chosen that if used, would satisfy as many of the publications addressed in section 2 as possible. Specifications were selected as those which were most common across the different publications. If there were few but wide-ranging specifications, the more conservative value was selected (as in unsupported wall length) or an average value (as in distance from corner of building to opening). The specifications selected are shown in Table 5 with justification for the selected values also given.

4.2.2. Technical details for earthquake resistant rammed earth house

Using the specifications given in Table 4, a set of building plans were developed for an earthquake resistant rammed earth house. Exploded view, floor plan and an isometric view have been produced using the information from Table 5 as shown in Fig. 3. According to Eurocode 8 [65] a number of aspects need to be considered at the conceptual design stage of a building in order for it to meet two key requirements for building in seismic zones, i.e. no collapse and damage limitation performance levels are attained. These include structural simplicity, uniformity, symmetry, bidirectional resistance and adequate foundations.

For structural simplicity, uniformity, symmetry and bidirectional resistance, the simple layout of the building seen in Fig. 2 shows that the building is perfectly symmetrical which takes account of uniformity and with the use of internal walls and buttresses, bidirectional resistance is achieved. The rammed earth walls will be produced to a height of 2.2 m with buttresses at spacings of 3 m which will add to the lateral resistance of the forces induced by seismic loads.

The overall floor area for this building will be 36.9 m^2. Additional rooms can be added as long as buttresses and overall wall lengths do not exceed the dimensions specified in Table 5. A reinforced concrete horizontal band will then be cast on top of the wall tying the foundation, plinth beam, rammed earth walls and horizontal band together using the vertical reinforcement bars. Reinforcement bars will be 12 mm diameter and position at the corner of every wall and 200 mm from the edge of each opening. Roof specifications will follow best practice but will be light as possible. Timber or bamboo can be used to create a truss to form a gable or pyramid (hip) roof. The roof should be securely connected to the horizontal band in order to tie the entire structure together which will help ensure that the upper part of the structure does not move independently of the lower part of the structure.

Foundations are specified as concrete in the publications however in rural areas and particularly non-government-built dwellings, low cost stone masonry is more common as a material. Strip footings will be 0.6 m wide and be a minimum depth of 0.5 m. A reinforced concrete plinth beam will be cast on top of the foundation and be of equal width to the foundation and 0.3 m above ground level. 0.3 m is the recommended height in order to protect the base of the rammed earth walls from flooding. Foundation design is well developed in seismic design with variables that are likely to affect their performance arising due to ground conditions and workmanship. General recommendations on site selection which is covered in many of the publications should therefore be followed.

4.2.3. Future work and validation of specifications

It must be noted that the above building specifications satisfy all 13 publications listed in Table 2. The issue with this is that different countries have different methods of classifying seismic zones, which in turn will affect any seismic design calculation. As this design went with the more conservative values, it is likely this house would be over designed for areas with low seismic risk and intensity. In order to verify the design of this rammed earth house, a finite element analysis of the building, subject to seismic forces should be carried out. Design specifications will be adjusted if necessary subject to these results to take account of different seismic zones. Alternate designs could be produced for different seismic zones to ensure buildings are not overengineered and therefore

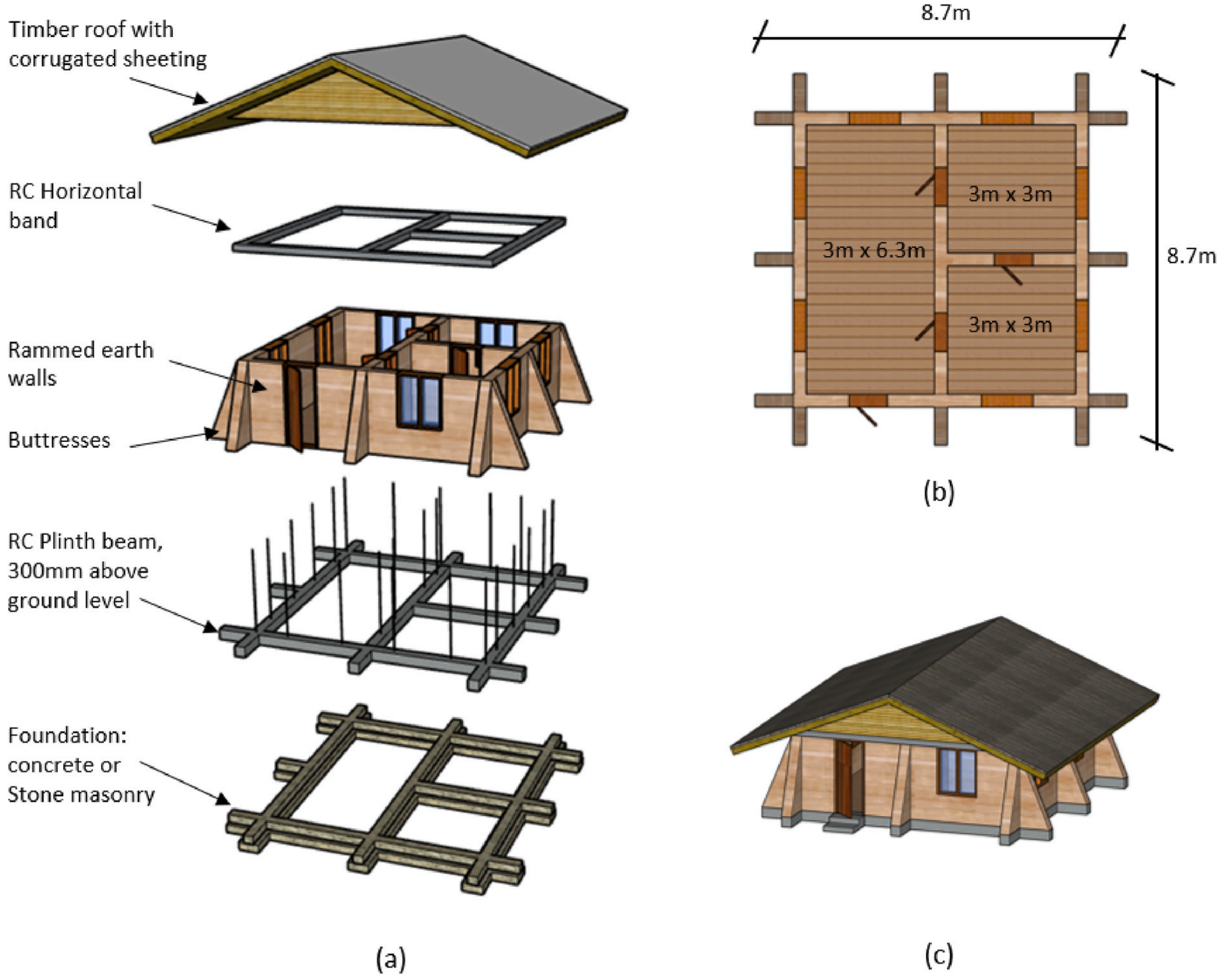

Fig. 3. Exploded view (a), plan view (b) and finished view (c), of proposed rammed earth house.

material use during construction is as efficient as possible. Future work may also include a review of the design in order to keep cost of construction as low as possible, while maintaining the required structural integrity.

5. Conclusions

A number of publications addressing rammed earth construction guidelines have been produced from many different countries. Due to the high number of people living in rammed earth houses around the world and the likelihood of many of these being located in seismically active zones, there is a need to have clear, concise and up to date information regarding the building specifications, utilising the expert knowledge available from those producing these publications and the various researchers around the world investigating rammed earth's ability to withstand seismic forces.

This review of rammed earth construction guidelines was carried out on standards, building codes and normative documents and those with seismic provisions were identified. The different specifications were identified and the differences between the guidelines were discussed.

Another issue identified was whether an engineer should be involved in the design of earthquake resistant buildings. Logically this should be the case but often engineers are not available in rural areas in developing countries where a number of these publications have their target users. To address this issue, a preliminary design for small, earthquake resistant rammed earth house was produced using specifications taken from all the publications reviewed and a visual representation was produced. Future validation of this design will be required in order to assess its performance when subjected to seismic loads.

It is hoped that this will be a step towards fully understanding the performance of rammed earth construction in seismically active zones in order to protect the lives of the people inhabiting them when future earthquakes occur.

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David Thompson: Conceptualization, Methodology, Investigation, Writing – original draft, Project administration. Charles Augarde: Writing – review & editing. Juan Pablo Osorio: Writing – review & editing, Supervision, Project administration

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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