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## Seismic Assessment of Rammed Earth Buildings: A Review

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### Abstract

Rammed Earth (RE) construction is an ancient green building method that is becoming popular because it is cost effective and eco-friendly. There are different approaches on how one can optimally assess the seismic vulnerability of rammed earth structures. This review aims to understand the parameters that govern the behavior of rammed earth construction in terms of its seismic threat, including the materials, reinforcements and the evaluation procedures. Some of the important techniques such as shake table, FEM, and DEM, to name a few, are described in order to demonstrate the behavior of a RE building during a seismic event. The study establishes that density, elastic modulus and compressive strength are the key material properties which determine the level of seismic resistance required for any particular use. The review includes additional methods of reinforcement, mesh wrapping and textile reinforced mortar (TRM) and the concrete column integration, which are known to enhance the structural performance of Rammed Earth buildings during earthquakes. In order to increase further the seismic resistance of rammed earth-based structures, the review points out the lack of standardized test methods, research on aging effects, as well as search for materials with better performance.

**Keywords:** IDA, Pushover analysis, Rammed earth, Seismic assessment, Vulnerability

### 1. Introduction

Rammed earth construction is a method of creating solid walls by compacting subsurface material occasionally stabilized with cement or other binders into successive layers inside temporary formwork (Maniatidis and Walker, 2008). It is also one of the most often used modern earth building techniques. Rammed earth constructions have been there since antiquity; researches conducted in Southwest Asia, Africa and middle east have shown structures dating as far back as 10,000 BCE (Silva et al., 2018). When the Iberian Peninsula was under Islamic rule, RE practices flourished between the eighth and thirteenth centuries (Silva et al., 2018). Roman Pliny the Elder first documented about rammed earth in 79 AD. In 18<sup>th</sup> century, François Cointeraux popularized rammed earth in Europe with his writings on "pisé de terre". During the 19<sup>th</sup> century, rammed earth techniques spread to the United States, especially in areas with limited timber (Gramlich, 2013). The locals in the Himalayan range like Ladakh in India, Mustang in Nepal, China, and Bhutan still practice traditional rammed earth construction (Shrestha et al., 2020). Figure 1 shows the areas of earth constructions all over the world.

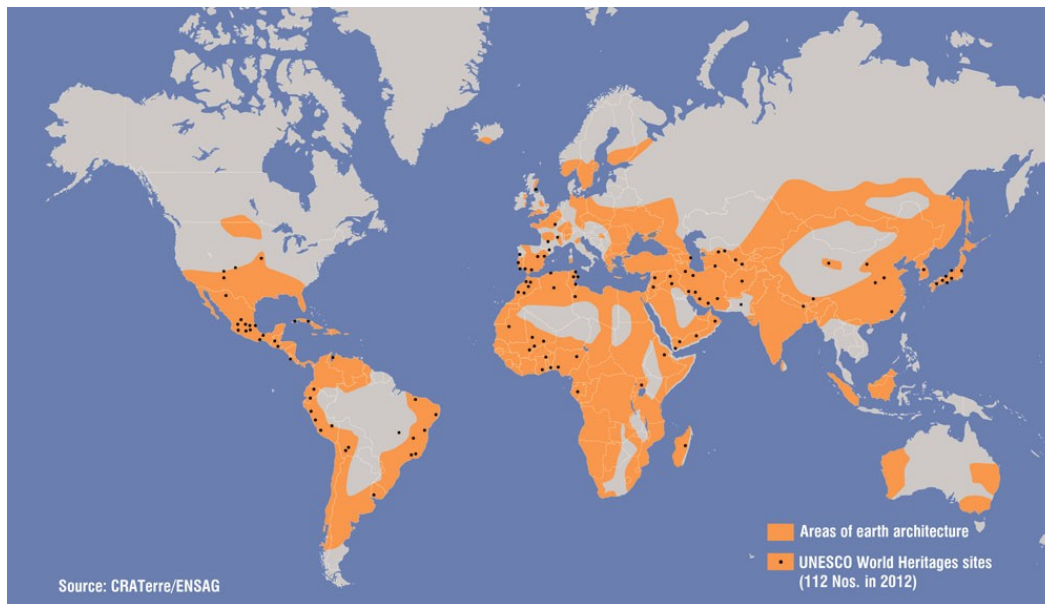


Figure 1: Areas of earth construction around the world (Correia et al., 2013)

## 2. Numerical Simulations and Experimental Validation

For seismic assessment, one of the most practiced techniques is the Finite Element Analysis (FEM). It permits detailed modeling of the entire displacement of structural components during an earthquake and its effects. Nowamooz and Chazallon (2011) used Cast3M software and FEM to model the non-stabilized rammed earth walls. They focused on L-shaped walls and analyzed the soil water retention, capacity as well as its tension. It was noted that drier walls are able to withstand higher cyclic loads. Using FEM models in DIANA software, Miccoli et al. (2016) used Cast3M software and FEM to model the non-stabilized rammed earth walls. They focused on L-shaped walls and analyzed the soil water retention, capacity as well as its tension. It was noted that drier walls are able to withstand higher cyclic loads.

DEM is another effective method to simulate the mechanical behavior of RE structures, simulating the interaction of discrete elements due to loading conditions, which is mainly needed in seismic performance. A research by Nabouch et al. (2016) evaluated the performance of RE walls using DEM. The analysis, in particular the force displacement relationship study, indicated that RE walls can be safely installed in the low to-medium seismic zone. The study also emphasized avoiding higher stories since these structures amplify seismic movement.

Bui et al. (2020) carried out the analysis of seismic performance by discrete element technique DEM. Both types of reinforced and unreinforced RE walls of one-storey and two-storey buildings under vertical and horizontal seismic loads were modelled. Seismic performance in rammed earth walls was enhanced by incorporating vertical steel rods. Higher the compressive strengths of the materials higher the increase in seismic performance.

A numerical study to investigate the in-plane seismic behavior of rammed earth walls was discussed by (Bui et al., 2018). Seismic performance assessment is a numerical study that models an in-situ RE by DEM and further scales earthquake excitation to assess the seismic behavior, keeping track of drifts for analysis.

In general, numerical models are a powerful tool in seismic performance studies since they can forecast the behavior of buildings subjected to seismic loads. However, such simulations need experimental data to validate them. For this reason, Ramezanpour et al. (2021) verified the FE

model of RE walls with quasi-static cycle testing. Indeed, there is effectiveness due to high accuracy because the experimental results are in good accordance with numerical predictions. To evaluate the dynamic behavior of rammed earth walls, Silva et al. (2018) combined destructive and non-destructive testing methodologies to investigate the dynamic behavior of rammed earth walls. It was underlined that an understanding of the failure mechanism and crack propagation is of paramount importance for having a proper view of seismic performance.

Shake table tests involve physically testing structures under earthquake conditions in order to generate data for real-life simulations. In the study by Zhou and Liu (2019) shake table testing was used in simulating the dynamic characteristics, including acceleration and displacement response, under seismic waves of two single-story, ½-scale rammed earth houses. From the results obtained, internal reinforcements improved seismic performance substantially.

Tetley and Madabhushi (2007) considers a discussion on the seismic performance of adobe structures to be relevant in showing how such can be improved by, among others, using plastic carrier bag mesh, wire mesh cages, and steel reinforcing bars. Seismic performance was tested with 1g shaking table tests on the 1:5 scale models of adobe walls comparing the failure accelerations between the better and the unimproved models.

Sen and Saha (2025) show that naturally fibre-reinforced retrofitting of rammed earth houses performs better during earthquakes and showed damage to the unreinforced and cement-stabilized rammed earth house models. One-way shaking table tests of the retrofitted rammed earth model houses without reinforcement.

### **3. Seismic Assessment Methods of Rammed Earth Buildings**

The seismic in-plane performance of rammed earth components and the efficacy of TRM strengthening to increase their seismic resistance are assessed in the work by (Allahvirdizadeh et al., 2019). The study employed incremental dynamic analysis (IDA) and pushover analysis as seismic performance evaluation techniques.

The in-plane seismic performance of mortar-strengthened rammed earth walls that are not strengthened and those that are reinforced with textile is investigated numerically in the study by (Allahvirdizadeh et al., 2019). Nonlinear finite element modeling, encompassing incremental dynamic analysis (IDA) and pushover analysis. Future experimental testing will be carried out in accordance with the results of the numerical modeling.

To characterize the seismic vulnerability of rammed earth walls, Romanazzi et al. (2022) empirically investigate their in-plane cyclic performance. In this paper, in-plane cyclic loading is imposed on a large-scale specimen of a rammed earth wall as part of the approach for seismic performance assessment, while dynamic identification tests were also conducted following the evolution of dynamic properties of the wall and structural damage.

The work by Pennacchio et al. (2022) aims at the influence of traditional construction practices on seismic vulnerability in Bhutanese Vernacular Rammed Earth architecture. The impact of traditional building practices on the seismic vulnerability of Bhutanese vernacular rammed earth architecture is examined in the work by the research cooperation between Politecnico di Torino, Nagoya University, and the Royal Government of Bhutan investigates the local building practice's influence on rammed earth buildings' seismic failure processes. A comparison of past damage assessment studies carried out by the Bhutanese government with

the conclusions reached by the researchers on earthquake failure mechanisms. Discussion of conventional building techniques, potential flaws and their effect on seismic failure mechanisms are carried out based on specific criteria. One of the research findings was verified through a full-scale static test carried out on a rammed earth mock-up building.

Static pushover experiments on RE walls by El-Nabouch et al. (2017) demonstrated that reduced vertical strains enhanced in-plane seismic performance, particularly in single-story buildings. The walls' ductile characteristic is advantageous for seismic resilience. The out-of-plane reaction of RE structures was the subject of studies such as (Allahvirdizadeh et al., 2019). They showed that load capacity was greatly increased by strengthening with textile-reinforced mortar (TRM).

#### **4. Reinforcement Techniques and Strengthening Strategies**

Since unreinforced rammed earth is brittle, reinforcement is usually added to improve seismic performance. According to Nabouch et al. (2016), rammed earth walls are unsuitable for high seismicity zones and require reinforcement for medium seismicity zones, but they can have enough seismic resistance in low to moderate seismicity zones. Nonlinear force-displacement curves for the rammed earth walls were obtained using discrete element modeling (DEM). Standard acceleration-displacement curves are generated in accordance with Eurocode 8. Superimposition of the force-displacement and acceleration-displacement curves to determine the intersection point (target point), which was then used to assess the seismic performance of the walls under different conditions (vertical load, seismic zone).

The seismic in-plane performance of rammed earth components and the efficacy of TRM strengthening to increase their seismic resistance are assessed in the work by (Allahvirdizadeh et al., 2019). The study employed incremental dynamic analysis (IDA) and pushover analysis as seismic performance evaluation techniques.

The effectiveness of two strengthening approaches and the seismic performance of a vernacular rammed earth building are evaluated in the paper by (Librici et al., 2017). Finite element modelling (FEM) was the seismic performance assessment method employed in this study to numerically characterize the seismic performance of a vernacular rammed earth construction and the effects of two strengthening techniques (a ring beam and textile reinforced mortar) on its seismic performance.

According to Sen and Saha (2025), rammed earth houses that have been modified with natural fiber reinforcement perform better seismically than those that are unreinforced and cement-stabilized. Unreinforced and retrofitted rammed earth model houses were used for unidirectional shaking table tests.

According to the research by Romanazzi et al. (2019), a TRM-based strengthening technique increases the shear strength and stress distribution of rammed earth structures, hence improving their seismic capability. Diagonal compression tests were used to evaluate the seismic performance of rammed earth wall specimens that were both unstrengthened and strengthened using the Textile Reinforced Mortar (TRM) technique, which uses glass fiber or nylon mesh embedded in an earth-based mortar.

The seismic performance of rammed earth walls can be enhanced by the addition of structural columns. A quasi-static experimental study comparing the effects of various structural column reinforcements on the failure shape, bearing capacity, deformation capacity, and energy

dissipation capacity of rammed earth walls was the seismic performance assessment method employed in (Zhou and Liu, 2019).

According to Romanazzi et al. (2023), a TRM-strengthening solution enhances rammed earth walls' ductility, energy dissipation, and in-plane shear capacity under cyclic loads. A strengthened rammed earth mock-up was tested under in-plane cyclic loads as part of an experimental program to evaluate seismic performance. Metrics like cracking, damage, displacements, base shear, stiffness, and energy dissipation were assessed, along with the use of simplified analytical models.

#### 4.1. Internal Reinforcement Techniques

- **Concrete Columns and Beams:** Nguyen et al. (2021) presented the influence of RE walls associated with reinforced concrete columns and beams. They concluded that such reinforcement elements had a significant effect on improving earthquake resilience, especially for multistory buildings.
- **Post-Tensioning:** Even though additional research is required in order to clearly define the technique Hamilton III et al. (2006) investigated the application of post-tensioned strengthening in RE walls concluding that it reduces deformations under seismic loading.

#### 4.2. External Reinforcement Techniques

- **Textile-Reinforced Mortar (TRM):** Allahvirdizadeh et al. (2019) utilized TRM reinforcement to enhance out-of-plane seismic performance of RE walls. They showed that TRM reinforcement improves in both displacement and load at failure thus providing a feasible solution to the problems of increasing the seismic resistance of RE structures.
- **Mesh-Wrap Strengthening:** Wangmo et al. (2021) conducted a study on the mesh-wrap strengthening of thinner layers of rammed earth for the improvement of both shear and compressive strength in RE walls.

### 5. Material Properties

Mechanical properties such as compressive strength, density and modulus of elasticity of rammed earth play a vital role in its seismic performance.

- **Compressive Strength and Density:** Research by Ramezanpour et al. (2021) showed that density, compaction, and the type of material used for constructing RE has significant effects on the compressive strength of the material. Higher density is usually characterized by higher compressive strength.
- **Elastic Modulus:** A study by Bui et al. (2020) illustrated the dependence of the values upon the soil type and moisture content, while also studying the empirical relations between compressive strength and elastic modulus.

Table 1: Mechanical Properties of Rammed earth in different research works

Research works	UCS (MPa)	Density (kg/m <sup>3</sup> )	Young's Modulus (MPa)
(Maniatidis and Walker, 2008)	2.46	1850	160
(Lilley and Robinson, 1995)	2	2170	
(Bui and Morel, 2009)	1	1800	90
(Miccoli et al., 2014)	3.73	2190	4143
(Allahvirdizadeh et al., 2019)	1.28	2000	1034

Research works	UCS (MPa)	Density (kg/m <sup>3</sup> )	Young's Modulus (MPa)
(Librici et al., 2017)	1	1723	67
(Ramezanpour et al., 2021)	1.17	1940	253.9
(El-Nabouch et al., 2017)	2		763
(Shrestha et al., 2020)	0.85	2028	79.3
(Wangmo et al., 2021)	0.98	1818	102
(Nguyen et al., 2021)	1.14	2104	243
(Bui et al., 2020)	2	2300	400
(Liu et al., 2015)	1.357	2020	57
(Arslan et al., 2017)	1.47		
(Zhou and Liu, 2019)	1.24	2104	243
(Nabouch et al., 2016)	0.97		
(Lepakshi and Reddy, 2020)		1800	
(Liu et al., 2015)	1.357		57

Table 1 shows the various mechanical properties of the rammed earth material in the research done in different settings. These properties play crucial role in the seismic performance of rammed earth buildings.

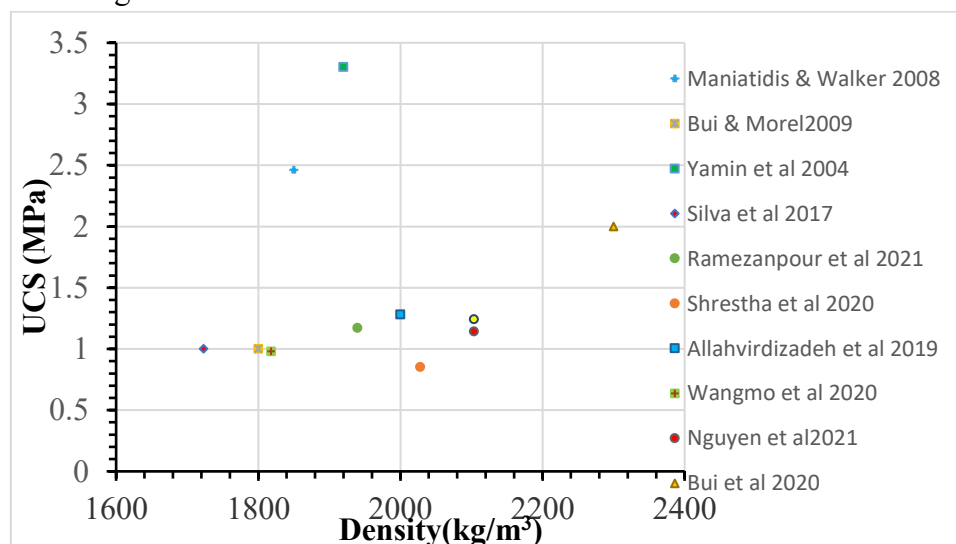


Figure 2: Compressive strength as a function of density

The graph in Figure 2 shows that density (kg/m<sup>2</sup>) and UCS (MPa) have a positive correlation. The compressive strength of rammed earth is usually high if density is also on the higher side. The chart shows notable changes in UCS for comparable densities between studies which may be due to difference in testing procedure or different sources of the material but more detailed research into the reasons underlying these variances is also necessary.

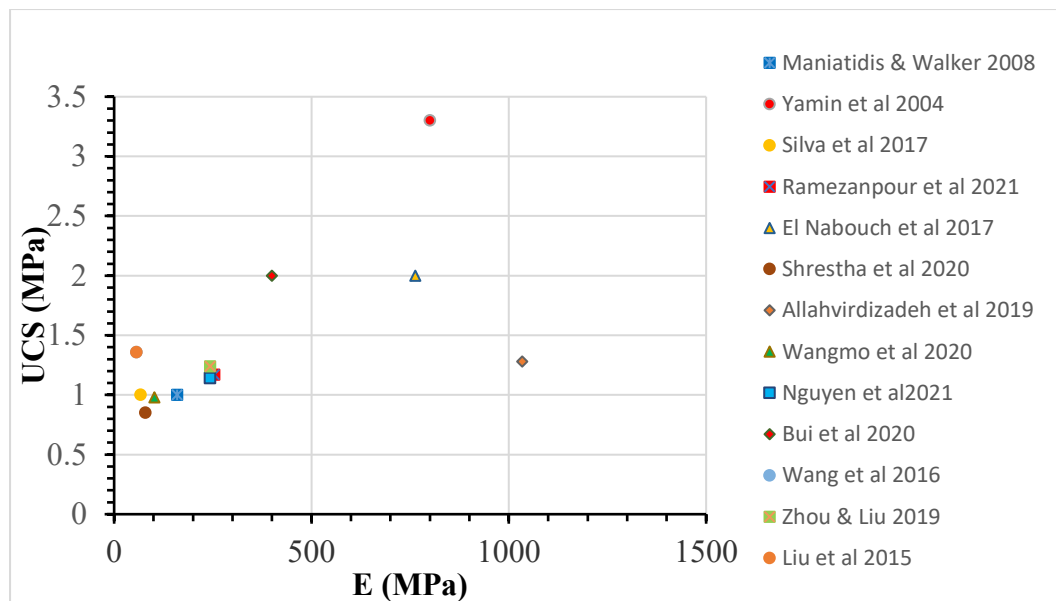


Figure 3: Compressive strength as a function of Young's Modulus

The relationship between Elastic Modulus (MPa) and UCS (MPa) from various research is displayed in Figure 3. Compressive strength and elastic modulus generally correlate positively. Figure 3 exhibits noteworthy variations in Elastic Modulus for comparable UCS values among many investigations suggesting the need for additional investigation to comprehend the fundamental elements behind this fluctuation. This can entail looking at how various soil types, moisture contents, and compaction methods affect the mechanical characteristics of rammed earth. Although the compressive strength values are highly dispersed, we can observe them in the range of 0.7 MPa to 3.5 MPa. These variations can be due to the composition, compaction, density, moisture content, size and shape of the samples being tested. Since there is not a single universally accepted testing procedure, researchers have adopted different strategies according to their local/regional standards and resources available to them.

The particle sizes adopted in various research works on rammed earth are shown in Figure 4. Ciancio et al. (2013) has given limits for particle size distribution and other research works were performed for earth material with PSD curve within these limits. The buildings constructed with rammed earth material having their PSD curves within the limits are expected to perform well during seismic events as well.

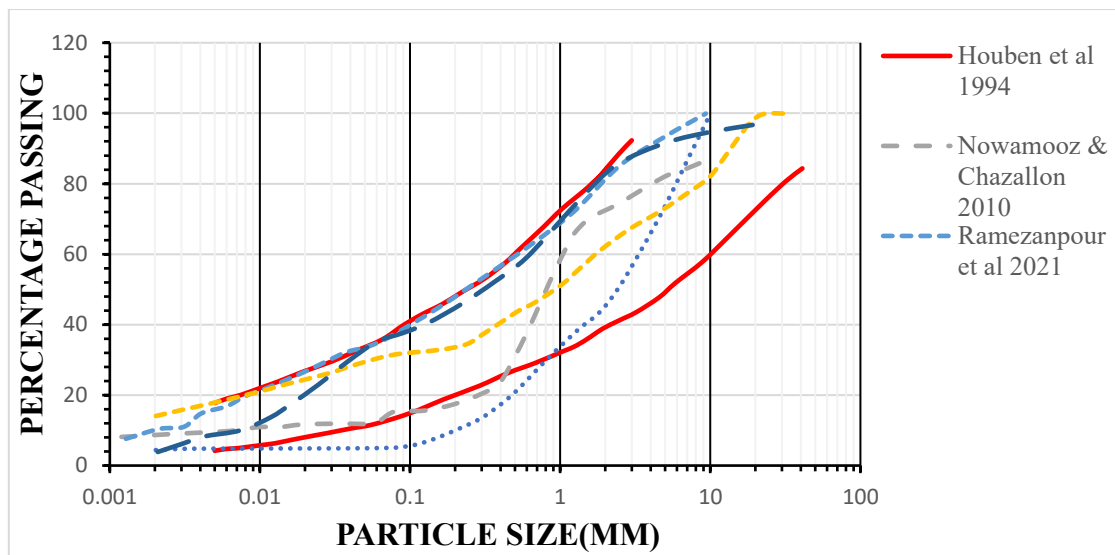


Figure 4: Particle size distribution curve for rammed earth material

## 6. Conclusion

Rammed earth (RE) construction has been known for its ecological benefits but its application in seismic zones has been quite difficult as this construction method which has historical significance lacks ductility and reinforcements. Computer programs or techniques such as Finite Element Modelling (FEM) or Discrete Element Modelling (DEM) are employed to design rammed earth structures and test the durability of these structures against seismic forces. These models seek validation through experiments such as key tests on shake table, which shows that using external reinforcements such as textile reinforced mortar (TRM) or using reinforcements in the form of concrete columns can significantly improve the seismic performance of these systems.

When looking at the overall effects of RE construction, one must consider the consequences of building material selection such as density and compressive strength as effective strength are also associated with these two features. Although all these can be enhanced through reinforcements, in plane loading situations tend to get most support, whilst out of plane loading instances are typically less stable.

The reinforcement techniques, such as mesh wrapping, post-tensioning, and TRM, have enhanced the resistance of the RE walls to seismic stresses by improving the ductility and shear strength of the RE walls. Certain aspects that require focus in future studies to further enhance seismic resistance in RE buildings are long-term performance, uniformity in testing procedures, and the incorporation of innovative materials. Further developments that could render rammed earth more viable and safer in seismic regions are also possible. Indeed, detailed investigations will be done for different typologies adopted all over the world to provide safety to its residents.

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