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Reliability analysis of rammed earth structures

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HIGHLIGHTS

- Reliability analysis for rammed earth structures is performed.
- Uncertainty is included in parameters contributed to resistance and loads.
- FORM, SORM and Monte Carlo Sampling method were used and compared.
- Random variables with most impact on the reliability index are specified.
- Recommendations are given for minimum compressive strength and wall thickness.

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ABSTRACT

Rammed earth (RE) structures are widely used for more sustainable and environment-friendly buildings. Due to lack of design standards, the engineering decisions often rely on rule-of-thumb method which may lead to quite conservative or unsafe designs. In this study, load and resistance parameters were treated as random variables in reliability analysis. The reliability index and failure probability of RE structures were evaluated using First-Order-Reliability-Method (FORM) and then compared with Second-Order-Reliability-Method (SORM) and Monte Carlo Sampling method. The analysis was performed based on the different a) load combinations, b) wall geometry, c) material type (unstabilized or cement stabilized) and d) mechanical properties of the materials. Based on the results, the RE wall under moderate loading conditions require smaller wall thickness than recommended wall thickness by various guidelines such as New Mexico-USA, New Zealand and Zimbabwe Codes. However, larger wall thickness is needed under severe loadings conditions, especially when unstabilized materials are used. The compressive strength of unstabilized materials under severe loading conditions should be more than minimum recommended. The sensitivity analysis was performed by calculating different importance and sensitivity vectors. The results show that the compressive strength and the environmental loads factors are the most important random variables that contribute to reliability of the structures. The recommended wall thickness and compressive strength for different conditions are presented.

1. Introduction

Nowadays, construction with earthen materials has become more widespread due to their advantages such as low construction cost, low embodied energy and recyclability of materials. It is estimated that near to one-third of the world population live in the houses made of natural soils like earth block (adobe) masonry, cob, and rammed earth (RE) [1,2]. Rammed earth houses have been used in all around the world for decades. They are built in many countries such as Australia, China, India and many parts of Africa and Europe. The rammed earth materials are cheap, tough, and green. These structures commonly used where skilled labors are not available, using modern technologies is not possible, and/or due to impassable roads the cost of transportation is relatively high. Earthen materials have great impact on reducing the environmental effects of industrial constructions and also have economical superiority by using in-site raw materials. However, they need continuous maintenance because of susceptibility to erosion, physical degradation and cracks under low tensile and shear stresses. Due to high mass, low ductility and low tensile and shear strength they are susceptible to high damages in areas with high or moderate seismic risk [2–4].

The rammed earth houses are typically supported by bearing walls and are generally low rise (single or two-story), although higher rammed earth structures have been built. The rammed earth structures are made of a mixture of soil (local earthen

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materials) containing a binder. The mixture of soil is prepared in near its optimum moisture content to maximize its dry density and is formed in temporary formworks in layers about 10 to 15 cm thick. The earthen material is then compacted by using manual or pneumatic rammers to have layers about 6 to 10 cm. The layers are increased up to the desired level. The soil composition varies greatly and is ideally sandy-clay gravel. Rammed earth structures are divided to two groups: Stabilized and unstabilized rammed earth. When the binder is just clay, this material is referred as "Unstabilized Rammed Earth" (URE) and when the binder is cement or lime, is referred as "Stabilized Rammed Earth" (SRE). The stabilization of soil improves mechanical properties and durability of the structure; however, it has detrimental environmental impact and increases the embodied energy [1,5,6].

The suitability of soils is typically checked based on the particle size distribution (percentages of clay, sand, and gravel) and Atterberg limits. The minimum compressive strength of the suitable soils are specified between 1 to 2 MPa in different guidelines [7–10], although higher values especially for stabilized materials have been gained. Because of variety of soil composition in different locations and not sufficient researches on the behavior of rammed earth structures, there is no comprehensive design and construction provisions for them with the same approach as for the steel and concrete structures. There are only some guidelines and handbooks which give mostly some recommendations and advices in this regard. Hence, the design of rammed earth structures are traditionally based on "rule of thumb" method and it may lead to large safety factors and increase in cost of structures. On other hand, it would result in unsafe shelters in area with severe environmental loads such as heavy snow loads, storms or ground motions [6,11–14].

The objective of this research is to perform reliability analysis on URE and cement stabilized rammed earth (CSRE) structures under dead, live, and relatively severe and moderate wind and snow loads. The results of probabilistic approach dealing with uncertainties is used to check the general recommendations on the wall thickness and compressive strength of materials. By performing sensitivity analysis, the random variable parameters which have most effect on the reliability index and strength of the buildings are determined. The recommendations about minimum compressive strength of materials and minimum wall thickness subject to common loads are presented.

2. Resistance random variables

In classical deterministic analysis, uncertainties are not included in structural design, and parameters are considered by their worst cases. Whereas, resistance parameters, applied loads, and the probability of the occurrence of them consist of randomness. To apply reliability concepts in analysis of the structures, it is essential to define the random variables and limit states precisely. Random variables describe the uncertainty and are modeled with given distribution functions and distribution parameters. Limit-state function defines the event for which the probability is considered [15].

In this section, the random variables which represent the uncertainties of the resistance of the URE and CSRE structures are discussed. The applicable probability distribution and required parameters for different resistance random variables are summarized in Table 1.

2.1. Compressive strength

The resistance of a RE walls supporting gravity loads and noncyclic transient loads is governed by the material compressive strength. It is impractical to have an estimation for the compressive strength based on the earthen materials composition without testing. The recommended values for unconfined compressive strength of RE material is varied between 1 to 2 MPa as per different guidelines [4,7,8]. Due to the influence of the applied compaction energy, variation of the moisture content of the materials with respect to the optimum moisture content, curing method of the materials, and using different soil compositions, the coefficient of variation (COV) of the compressive strength is relatively high especially for unstabilized soils. By brief review on the past researches [2,5,12,16] and also the tests performed by the authors, the COV for URE and CSRE materials were 35% and 22%, respectively. The proper probability distribution to model compressive strength which avoids negative possible values is Lognormal [17]. Here, four different mean values of 1, 1.5, 2 and 2.5 MPa were considered to assess the effect of compressive strength on the performance of rammed earth structures.

Table 1
Resistance random variables parameters.

Random Variables	Distribution	Mean Value	COV (%)
Compressive strength of URE walls (MPa)	Lognormal	1,1.5,2, and 2.5	35
Compressive strength of CSRE walls (MPa)	Lognormal	1,1.5,2, and 2.5	22
Humidity effect of External walls	Uniform	0.75	19.24
Humidity effect of Internal walls	Uniform	0.95	3.03
Smoothness factor of External walls	Normal	0.9	5
Smoothness factor of Internal walls	Normal	0.95	2
Erosion factor of URE walls	Gumbel	0.016	25
Erosion factor of CSRE walls	Gumbel	0.005	20

2.2. Wall thickness

A minimum wall thickness is one of the main influence parameters provided in the guidelines and handbooks. The minimum recommended wall thickness varies for different design standards. A summary of some recommendations are shown in Table 2. Different thicknesses were used in this study to evaluate the performance of the walls under different conditions. The internal wall thicknesses were 125, 200 and 250 mm and the external wall thicknesses were 250, 300 and 400 mm for external walls. In addition, internal walls made of URE materials with 2 MPa compressive strength were analyzed for 150 mm thick walls under moderate loads.

For most cases the surface of the wall is not smooth, and the wall thickness just after removing the formworks and during the lifetime may not be exactly equal to the designed thickness. The reason is due to large particle size grains and not heavy interlock between ingredients which causes the wall thickness be smaller than expected. Therefore, based on engineering judgment, to consider the smoothness of walls in reliability analysis, a reduction factor with normal probability distribution was used. The mean and COV were 0.9 and 5%, respectively.

Table 2
Recommended wall thickness based on different standards.

Reference	Thickness of Wall (mm)	
	Internal	External
Standards Australia [8]	125	200
New Mexico Code [18]	300	450
Standards New Zealand [7]	250	250
Zimbabwe Code [19]	300	300