Earth as a building material for reproduction of ancient buildings in China Meishan cultural park

Jinge Luo[1]*, Xiaofei Wang[2], Junhui Luo[3]

[1]*School of Arts and Design and School of Architecture, Hunan University, Changsha, 410082 China*

[2]*School of Civil Engineering, Dalian University of Technology, Dalian 116024 China*

[3]*Institute of Geotechnical Engineering, Southeast University, Nanjing 210096, China*

**Corresponding author's e-mail: jinge.luo@gmail.com*

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Abstract

Rammed earth was vastly used for ancient buildings in the Meishan region in the central south part of China. However, these rammed earth buildings are rarely found nowadays. During the construction of Meishan Cultural Park, a park that reproduces the ancient architectures and cultures of Meishan region, the rammed earth architectures need to be reconstructed. In this paper, preliminary designs of these buildings were investigated. Specifically, the procedures to build the wall and to select the soils were introduced first. Then the seismic resistance behaviours of a typical rammed earth building in the ancient Meishan region was investigated using finite element modelling. The designed rammed earth walls were found to be able to satisfy the strength requirements of modern building standards. This paper also shows that the modelling of rammed earth buildings can be geotechnical in nature, as opposed to simply structural analysis.

Keywords: Rammed earth, Soil selection, Ancient buildings, Cultural park, Finite element modelling

1 Introduction

The rammed earth buildings have been constructed widely in the rural area of Human, China because of the availability of these construction materials and their good performances of maintaining indoor weather including temperature and humidity etc.. Air humidity in a room has a significant impact on the well-being of inhabitants and earth is one of the best material to balance indoor humidity (Pacheco-Torgal and Jalali 2012). This is because that earth material is a porous material that has the capacity to absorb and desorb from air and thus is able to balance the indoor humidity. The effectiveness of this balancing depends on their speed of absorbing and desorbing. In other words, rammed earth is a green material with high energy efficiency.

Two key issues regarding the reproduction and potential revival of this type of buildings are that: 1) selection of suitable soil types that can be used for rammed earth construction; 2) such structures that made of local soil are often susceptible to earthquake damage because of their heavy weight and low strength (Liu et al. 2015).

This paper firstly proposed a building procedure of using local earth to build the walls. The processes of the local earth and the mix design of the wall material were investigated. Secondly, a typical rammed earth structure in the cultural park under seismic loading was simulated using ANSYS (ANSYS Inc, Canonsburg, PA, USA) and ABAQUS (Dassault Systemes, France) and the deformations of the building were analysed.These guidelines, written in the style of a submission CM&NT, discuss how to prepare your paper using Microsoft Word. In addition to the usual guidance on style/formatting, there are notes and links to assist in using some of Word's features such as inserting graphics, formatting equations and so forth.

2 Methods and Materials

2.1 THE BUILDING PROCEDURES OF RAMMED EARTH WALL

Every building has many components such as the walls, the roof and the floor amongst others. But in the context of the rammed earth building, the walls are the most important structure that peoples are interested in.

The supporting base (i.e., foundation) for traditional rammed walls normally are constructed using stones gathered from the locality of the building site. These supporting bases not only provide support for the walls but also prevent the wall from being affected by the adverse effects of ground water. In this design, stones were used keep in line with the traditional design methods. Of note, this kind of supporting base was proved to be strong enough to bear the loading of the whole building.

FIGURE 1 The forms and rammer used to build rammed earth walls in southern China

During the building of the wall, each form is filled first, then another form is placed above it, and the process begins again. This process is repeated until the wall finished. The lower forms can be taken off as soon as the form above is begun. Pneumatic rammers were used to compact the earth within the forms. Figure 1 shows the forms and the rammer used to build the rammed earth wall in south part of China.

2.2 SELECTION OF SOIL

The composition of soils in different regions varies considerably due to the origin and the climatic conditions. It was shown that rammed earth allows a wide variety of soils with different composition. However, careful selection of soil is still necessary to control its quality.

In China, there is no official code that provides guidelines for the selection of soil for rammed earth. In this project, we used the maximum and minimum values of content of clay, silt, sand and gravel that are recommended to aid selection by (Shang 2005, Steve 2010). Extensive experiments have shown that as long as each substance is in the recommended range, the strength and durability of the earth wall are likely to meet the requirements. In this project, sandy loam sub-soils directly taken near the construction site were used. Topsoil is not used because it contains too much organic matters and it is highly compressible. The substances designed for this project are: clay (20%), silt (20%), sand (30%) and gravel (30%). A detailed study carried out at University of Bath indicates that the compressive strength of about 1.0–3.0 MPa can be obtained with unstabilized rammed earth (Maniatidis and Walker 2003) easily.

The mechanical behaviour of rammed earth ware affectted by various factors. Compaction is the most important factor that influences its stiffness. One significant factor that influences the compaction is the moisture content. If moisture is not enough, the wall may not have sufficient green strength to be able to withstand the mechanical disturbances mainly during the installation or uninstallation processes of forms. If there is too much water in the soils, the soil may become very sticky and may hamper the compaction process. The water content can also affect the density to a certain extent. The water content used in this project is 10% according to previous research (Bahar et al. 2004). The water content can be tested through a simple drop test in situ, which is demonstrated very useful (Morel et al. 2001). In the drop test, a ball of soil is made in the palm and then the ball is dropped on to a floor, from about one meter height. If the ball breaks into four to five pieces, the water content is good. If it crumbles away, the soil is too dry or if it stays as one pat, it is too wet.

In summary, this project will use the proposed mix design of clay, silt, sand and gravel and the water content of 10%.

3 Finite element modelling of a typical rammed earth building under seismic loading

A typical rammed earth building that is going to be built in China Meishan Cultural Park was used for this study. The building is a one-story building which is a wildly used building type in ancient Meishan region. These kinds of buildings were mainly used for the ancient tea industry.

In this study, response spectrum analysis and time history analysis were performed to evaluate the structural behaviours of the rammed earth building under seismic loadings. Response spectrum analysis is fast and is recommended by the design code of China. However, time history method can give more accuracy information including all sources of the nonlinear and time dependant material geometry effect although it is very computational expensive. Therefore, it is better to use the two methods combined to investigate the design of the rammed earth building. In this section, finite element modelling (FEM) was used to perform these studies.

3.1 GEOMETRY

The height of the building is 8 m and the wall thickness is 240mm. One door (900mm×2100mm) and four windows (400mm×600mm) were placed on the front wall. The architectural design of the building is shown in Figure 2. In the finite element analysis, only the rammed earth building was considered. The adjacent lower building was not considered.

FIGURE 2 Geometry of the rammed earth building (left)

3.2 MATERIAL PROPERTIES

The rammed earth material is treated as a homogeneous and isotropic material. This hypothesis has been proved to be adequate to model the rammed earth in a previous study (Bui et al. 2009).

Rammed earth can be modelled using the Mohr-Coulomb failure criterion (Nowamooz and Chazallon 2011). Mohr-Coulomb model is an elastic-perfectly plastic model, which is often used to model soil behaviour in general and serves as a first-order model. The stress-strain curve in the elastic range is linear with two parameters: Young's modulus, E and Poisson's ratio, ν.

In the Mohr-Coulomb failure criterion, the material failure is controlled by the maximum shear stress, which depends on the normal stress. The Mohr-Coulomb criterion can be written as:

$$\tau = c + \sigma \tan\phi , \quad (1)$$

where τ is the shear stress, σ is the normal stress, c is the cohesion of the material, and ϕ is the material angle of friction.

The material constants used for the rammed earth are: Young's modulus E = 60MPa, Poisson's ratio = 0.3, cohesion c= 150kPa, friction angle = 45 degrees， angle of dilation = 0 (Jaquin et al. 2006).

The roof was mainly made of wood. Therefore, the material properties of wood were used for the roof with a elastic modulus of 100 MPa and Poisons' ratio of 0.3. The density of the roof was 710 kg/m3 (Tankut et al. 2014).

3.3 MESHING

The geometry of the building used to simulate the seismic behaviours were discretised into 8,461 8-node hexahedral elements (Figure 3). All the parts in the finite element model were connected by sharing their boundary nodes. The mesh density was proved to be fine enough to provide reasonable accurate results.

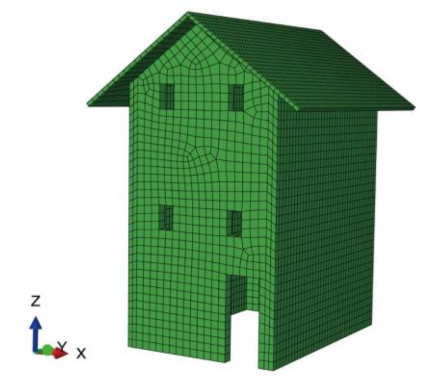

FIGURE 3 Finite element mesh of the rammed earth walls and roof

Two simulations were performed to investigate the seismic behaviours of this rammed earth building. Firstly, a model analysis was used to determine the frequency of the building. Response spectrum analysis, which is recommended by the China design code for normal buildings (GB5001 2001), was performed based on the model analysis results. Secondly, ground acceleration data from a rare earthquake was applied to the structure directly. The detailed loading scenarios were introduced below.

3.4 RESPONSE SPECTRUM ANALYSIS

Response spectrum analysis is a simplified method to evaluate the rammed earth building under seismic loading. There are two steps in running a response spectrum analysis. First a modal analysis was needed to obtain the modes of the structure. Secondly response spectrum analysis was performed using the models obtained in the model analysis as inputs. ANSYS Workbench (Ansys Inc., Canonsburg, PA, USA) was used to obtain the natural frequency and mode shapes of this building.

In response spectrum analysis, the key step is to make a response spectrum. In this paper, a standard response spectrum recommended by The China code for seismic design of buildings (GB5001 2001) was used. The response spectrum is shown in Figure 4.

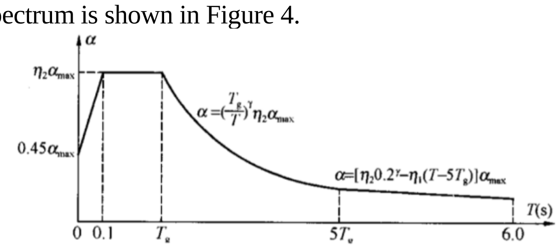

FIGURE 4 The standard response spectrum recommended by China design code (GB5001 2001)

The parameters used in the response spectrum curve are determined by the site class and building class etc.. These parameters can be determined from China code for seismic design of buildings (GB5001 2001) and seismic ground motion parameter zonation map of China (GB18306 2008). The parameters are listed in Table 1. The final response spectrum (Figure 5) was obtained based on these parameters.

TABLE 1 The parameters used to determine the response spectrum

Parameters	Values
α_{max}	0.04
η_1	0.02
γ	0.9
T_g	0.35
η_2	1

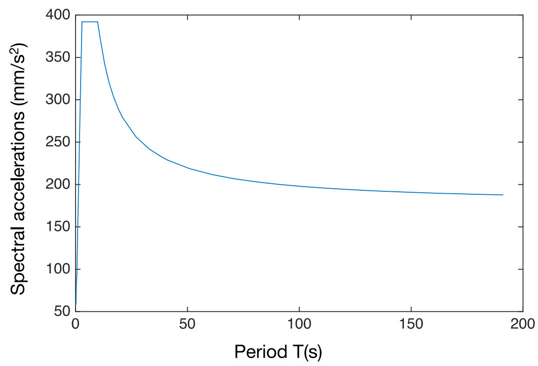

FIGURE 5 Response spectrum of seismic acceleration according to China design code(GB5001 2001)

3.5 TIME HISTORY ANALYSIS

In the response spectrum analysis, only the elastic behaviors can be included. In order to see the rammed earth building's plastic deformations and to see the building's strengths under very rare earthquakes, a time history analysis was performed. In the time history analysis, ground motion recordings of the 2008 Wenchuan Ms8.0 earthquake was applied on the building to examine the buildings behaviors under extreme loading conditions. The ground data used in this research was observed at a station that is about 100 km from the epicenter as illustrated in Figure 6.

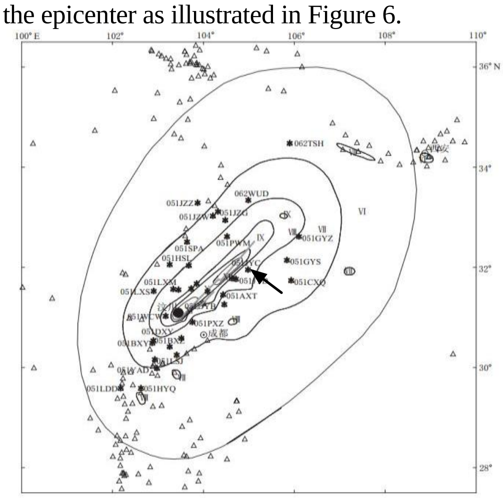

FIGURE 6. The seismic ground acceleration data used in this study was observed at the Jiangyou station as indicated by the black arrow.

The original ground motion data (Figure 7) were smoothed using a Butterworth low pass filter and then resampled to reduce the data points to allow a reasonable computational time in the simulation. Only the most detrimental part (with high acceleration; 36 seconds) of the ground data was applied to the structure in the simulation (Figure 8).

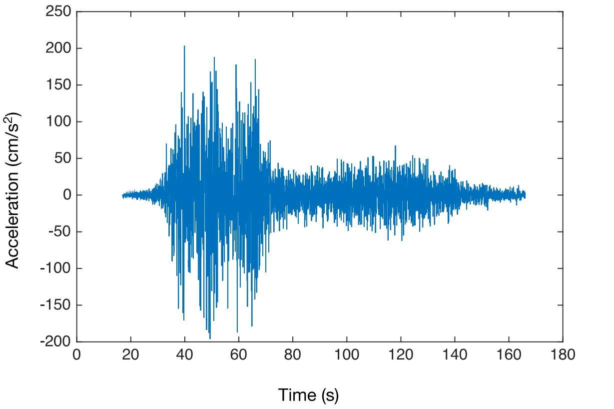

FIGURE 7 The original ground motion recordings of the 2008 Wenchuan Ms8.0 earthquake

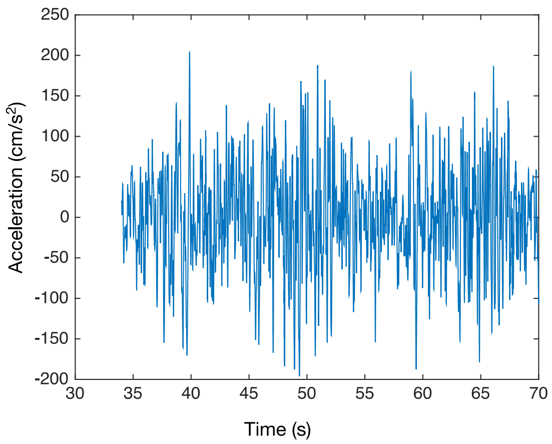

FIGURE 8 The ground acceleration data used in this analysis. Note that only the most detrimental section of the original data was used

Before any seismic loading, an initial stress state corresponding to the gravity load was applied to the structure. The ground acceleration was applied to the horizontal direction of the building (x direction in Figure 3).

4 Results

4.1 RESPONSE SPECTRUM ANALYSIS

Because the ground acceleration is applied in the x-direction in the response spectrum analysis, one needs to make sure that the effective mass in the x-direction is higher than 90% of the total mass. In the mode analysis, the results show that by requesting 8 modes there was 100% participating mass in the x-direction, which meets the requirements for the response spectrum analysis. Moreover it is found that 1 of the modes (mode 1) are contributing with 90% of the effective mass and consequently is can be expected that the earthquake response will be dominated by the first mode. The frequencies and are listed in Table 2. The first three vibration modes are illustrated in Figure 9.

TABLE 2. The frequencies of the rammed earth building.

Mode	1	2	3	4	5	6	7	8
Frequency	1.4146	1.4619	1.9946	2.2163	2.8516	2.8934	2.9247	2.9792

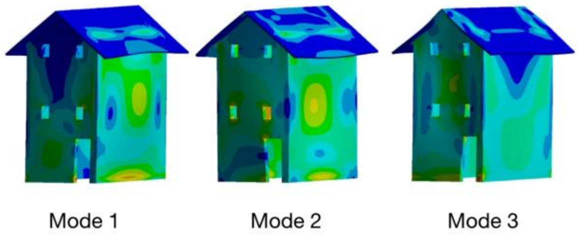

FIGURE 9 The first three vibration modes of the rammed earth building

The results of the x direction (horizontal) displacement of the rammed earth walls are presented in Figure 10. The middle part of the sidewall experienced the largest deformation. However, these deformations are relative small and will not affect the safety of the building. The stress levels were all way smaller than the yield stress. Therefore, the rammed earth walls meet the requirements of the China design code for normal buildings (GB5001 2001).

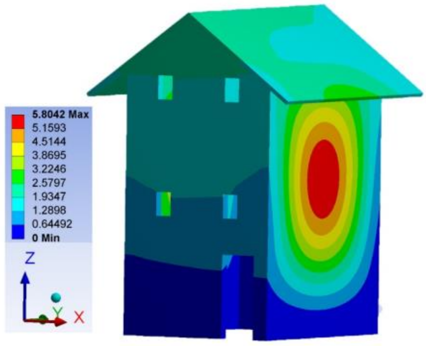

FIGURE 10 The x displacement of the rammed earth building (Unit: mm)

4.2 TIME HISTORY ANALYSIS

Because the ground accelerations of an extreme rare earthquake were applied on this structure, plastic deformations start to appear in this rammed earth wall after 36 seconds of seismic loading. The plastic strain distribution of this building under rare earthquake loadings is displayed in Figure 11. The von Mises stress distributions were also shown in Figure 12. The plastic strain is a good indicator to understand where plasticity yield occurs. One can observe, at the end of the step (36s), that plastic strains appear near the center and bottom of the sidewall.

The equivalent stresses were larger at the sidewall and the front wall, especially near the door and the windows. The plastic strain was not observed at the back wall in this building. Therefore, under extreme loading conditions, the building will experience plastic deformations but plastic deformations only present at a very small part of the walls. It should be noted that in this time history analysis, the seismic loadings were from an extreme severe earthquake and thus were way larger than those of the response spectrum analysis. Therefore, their results should be different.

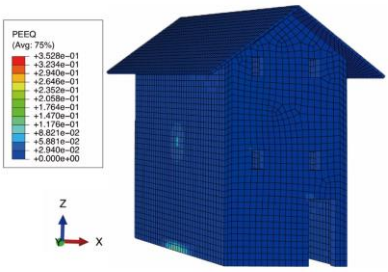

Figure 11 Plastic strain distribution in the rammed earth building under a rare earthquake

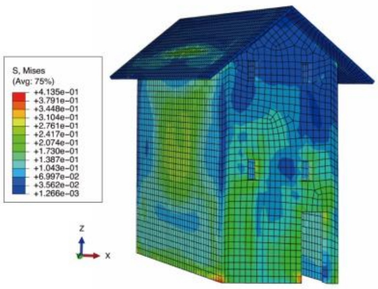

Figure 12 Von Mises stress distribution after a rare earthquake loading

5 Conclusions

This paper proposed a preliminary design of rammed earth buildings in China Meishan region. The proposed design can use the affordable, locally sourced sustainable construction materials. The proposed design of using rammed earth is of useful for rescuing the heritage and also it will promote the use of a rediscovered environmentally friendly building material.

A typical rammed earth building under seismic loadings was simulated through response spectrum analysis and time history analysis. The numerical modelling was performed with ANSYS and Abaqus finite element code. The designed rammed earth building is safe under the most possible earthquake conditions in that region and it is also safe under an extreme rare earthquake.

In this paper, the rammed earth was treated as a homogeneous single-phase material. Mohr-Coulomb failure criterion was used in the time history analysis. However, the rammed earth wall can be two-phase (soil and water). To become useful in the building field, rammed earth requires standards which will have to take into account the complex hydro-mechanical behaviour of this material. Therefore, the analysis of rammed earth building can be geotechnical in nature, rather than simple structure analysis.

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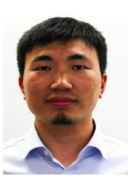
Authors

Jinge Luo, 1986, China

Current position, grades: PhD candidate
University studies: Architecture
Scientific interest: Architecture, Rural Buildings, Construction Technologies
Publications: 3
Experience: PhD candidate in Human University, China, research filed is rural buildings in Hunan province, China, experience in designing of modern and ancient buildings.



Xiaofei Wang, 1987, China

Current position, grades: Master student
University studies: Structural Engineering
Scientific interest: Concrete Structure, New Construction Materials
Publications: 4
Experience: a bachelor degree of Civil Engineering, experience in computational simulation and experimental research on novel concrete structure and rammed earth structures.

Junhui Luo, 1984, China

Current position, grades: PhD candidate
University studies: Geotechnical Engineering
Scientific interest: Soil Mechanics
Publications: 4
Experience: research on soil and rock mechanics for many years, computational and experimental experiences of research on soil structures.