

# Seismic Assessment of Rammed Earth Walls using discrete element modeling

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### Abstract:

Rammed earth (RE) is a construction material which is manufactured by compacting soil by layers within a formwork to build a monolithic wall. RE material is the subject of numerous scientific researches during the last decade because of the significant heritage of RE buildings and the sustainable properties of this material: low embodied energy, substantial thermal inertia, and natural regulator of moisture. The seismic performance of RE buildings is an interesting topic which needs to be thoroughly investigated. study assesses The present the seismic performance of RE walls by using the discrete element modeling (DEM) and the nonlinear pushover method. Firstly, nonlinear "forcedisplacement" curves of the studied wall were obtained by DEM. Secondly, the standard "acceleration-displacement" curves were carried out following Eurocode 8. Thirdly, the above curves were superimposed to determine the intersection point (target point) which enabled to assess the seismic performance of the studied wall in the corresponding conditions (vertical load, seismic zone).

# Keywords: rammed earth; seismic performance; discrete element method; pushover; sustainable development

## I. Introduction

Rammed earth (RE) dwellings are widespread in underdeveloped rural areas of western China,

which has several advantages over other buildings, including low cost, easy availability, thermal comfort, and low intervention with surroundings. However, RE constructions have drawbacks of sensitivity to water, propensity to shear failure, and lacking systemic engineering design concerning earthquake. They are susceptible to earthquake damage owing to low compressive strength, shear strength, and durability [1–3].

Many efforts have been undertaken to enhance the mechanical properties of rammed earth. [4-5] investigated the influence of nanotechnology on material characteristics of rammed earth, and the results showed that nanoclay could increase the level of compressive strength in rammed earth walls and be used as a cohesive material in the soil mixture. [6-7] studied the relationship among soil density, moisture content, and compressive strength and found that the compressive strength of rammed earth was very sensitive to its dry density and moisture content. [8] conducted an experimental study of the shear strength of a stabilized RE material reinforced with sisal and flax fibres. The results showed that a shear failure of the triplet test appeared along the weak interface between layers, but specimens failed along diagonal shear plane at the triaxial test.

Cite this article as: Bhukya Shanker, Kore Renuka, Sunchu Srilatha & Mhetre Likitha, "Seismic Assessment of Rammed Earth Walls using discrete element modeling", International Journal of Research in Management Studies, Volume 3, Issue 10, 2018, Page 1-8.



[9] conducted a study to investigate the influence of fibre length and fibre fraction on compressive strength, flexural strength, and shear strength of rammed earth. The results proved that adding straw could decrease shrinkage damage, reduce the curing time, and improve the mechanical property. In [10] analyzed the role of the moisture content on the mechanical characteristics and illuminated the importance of suction to RE specimens. There are limited numbers of studies on the improvement of the performance of earth buildings rammed using various reinforcement technologies. In [11] studied the effect of the split-level construction or pin keys on shear strength of rammed earth walls and found that the two methods were effective in improving the shear strength of construction with respect to the traditional method.

Generally, many experimental investigations have been conducted to enhance the mechanical properties of rammed earth by improvements in material characterization (chemical, physical, mechanical, and durability) and possible additions (lime, cement, straws, and fibres). However, there are limited investigations addressing the issues of the attempt to enhance seismic performance of rammed earth buildings by means of structural strengthening solutions. In this paper, precast concrete tie columns and precast concrete tie beam (tie bar) were proposed to improve the seismic behavior of RE constructions, and the effectiveness of these structural strengthening solutions is validated by conducting cyclic loading tests. The test results could provide data to support the RE construction practices.

### II. Pushover method



Fig. 1. Pushover analysis processing.

Pushover is a nonlinear static method which is from the displacement-based approach and currently used to assess the seismic performance of the structures [10]. The processing is summarized in the Fig. 1. First, the standard acceleration spectrum  $S_a$  is transformed in acceleration-displacement ( $S_a$ - $S_d$ ) format (Fig.1a), where  $S_d$  is the response spectrum in displacement:

$$S_{ij} = \frac{T^{2}}{4\pi^{2}}S_{ij}$$
(1)

The capacity curve - presented by the relationship between the shear force V and roof displacement d - is also established in  $(S_a-S_d)$  format where the shear force V is converted to the maximum acceleration  $S_a$ , and the displacement on top of the wall is converted to spectral displacement  $S_d$  (Fig.1b).

The intersection point D between the capacity curve and the demand spectrum (Fig.1c) is called the performance point. From the performance



point, the seismic demand and the damage states of the structure can be assessed

# **III. Experiments**

## A. Specimen manufacturing

RE walls were constructed in the laboratory by the laboratory's staffs who had already had a training (2 days) with a RE professional. Two types of wall were manufactured. Two walls had 1.5 m height  $\times$  1.5 m width  $\times$  0.25m thickness representing a wall of 3m-height and 0.5m thickness - the current case for RE buildings in France. Two other walls had the same width and thickness but had 1.0 m height, to study the influence of the height/width ratio on the in-plane seismic performance of RE walls. The used earth was provided by a professional RE builder. The water was added to the earth to obtain the optimum manufacturing water content (approximately 12% by weight). The mixture was then poured in a steel formwork and compacted in layers by using a pneumatic rammer. The wall was built on a 0.25 m  $\times$  0.25 m  $\times$  1.8 m concrete beam. After the wall construction, another 0.25m  $\times 0.25 \text{m} \times 1.8 \text{m}$  concrete beam was placed on top of the wall. This beam enables to apply a horizontal load on the wall top during the pushover test. Before putting the concrete beam, a thin lime mortar layer was added on the top surface of the wall to increase the bonding between the wall and the beam, Fig. 3b.

For each wall, a prismatic specimen  $(0.25m \times 0.25m \times 0.5 \text{ m height})$  was also manufactured for the uniaxial compression test. The dimensions of these specimens were chosen to reproduce compaction energy applied on the walls. The representativeness of the specimens was discussed [12]. The walls and the specimens were unmolded

after the construction and let to cure at the laboratory ambient conditions (20 °C and 60% RH) for two months. This is the time necessary to obtain quasi-dry specimens [13]. The moisture contents of all walls and specimens at the test moment were about 3 %.

# B. Experimental devices

The experimental device consists of a steel loading frame where the beams and columns have HEB400 cross section. The bottom concrete beam was fixed to the steel frame by four steel brackets that can be mechanically adjusted to have a correct embedment, Fig. 3a. Another steel jack (SJ on Fig. 3a) was used as support to prevent the beam sliding when applying the top horizontal displacement. The bottom concrete beam was also maintained by vertical tie rods to avoid the beam rocking.

Displacement sensors M1 (vertical) and M2 (horizontal) were used to check if there is any movement of the bottom concrete beam during the test (Fig. 3a).The displacements measured by the horizontal sensor M3 are used to verify the accuracy of the results obtained from the DIC (digital image correlation).

For a pushover test, first, vertical loads were applied on the top of the wall to simulate the vertical loads in a building (dead and live loads). Two electrical actuators VE1 and VE2 were used to apply these vertical loads. These loads were applied at a rate of 1 kN/s until 60 kN in each actuator. These vertical loads were maintained constant during the horizontal pushover. They represent a normal stress of 0.3 MPa which is the current case of RE walls in a 2 stories house. These loads were distributed on the top concrete beam through a system that includes a UPN 300



steel profile and cylindrical rolls placed at the top surface of the upper concrete beam (Fig. 3b).



# Fig. 2. (a) Test setup on a RE wall (1.5 m $\times$ 1.5 m $\times$ 0.25 m), (b) System placed on top of the beam.

Then, the horizontal pushover was carried out by a hydraulic actuator (VH) with displacement control, Fig. 2a. The loading rate was 1 mm/min up to failure. The horizontal load simulates a horizontal seismic action in the plan of the wall.

Uniaxial compression tests were also performed on the prismatic specimens which gave a mean compressive strength of 0.97 MPa. This compressive strength is closed to the results presented in the previous studies where specimens were manufactured by RE professionals.

The DIC was performed by using a professional camera with a resolution of 16 Mpixels. The DIC data processing was performed with the 7D software which was developed by Vacher et al. The displacement fields were determined by comparing the images after and before the loading (reference image). The DIC enabled to determine the displacements and the cracking development during the test.

# 3.3. Results

Fig. 3 shows the horizontal force in function of the horizontal displacement on top of the four walls. These displacements were obtained from the DIC which was more accurate than the displacement given by the horizontal actuator (influenced by the stiffness of the steel loading frame).

The curves in Fig.3 indicate the similar stiffness for the tested walls at the beginning of the horizontal loading (before 10 kN). It was also observed during the test that none of the tested walls had a brittle behaviour; after the test, the walls still support the concrete beam and could be transported by elevator without collapse

Walls 2 and 3 which have the same height (1.5m) exhibit similar behaviours: a maximal horizontal load about 40 kN and a ductile behaviour. Walls 1 and 4 having the same height (1.0m) but presented different behaviours. Wall 1 had a maximal horizontal load close to that of walls 2 and 3 but no ductile behaviour was observed. Wall 4 had a maximal horizontal load clearly more important than the other walls. A better behaviour of wall 4 comparing to walls 2 and 3 could be expected due to its lower height (less important flexural moment at the bottom section). However the net difference between wall 4 and wall 1 was relatively surprising. It could be suggested that the manufacturing of wall 1 was less well controlled than the other walls, since it was the first wall constructed and the laboratory's staff had less experiences.





# Fig. 3. The variation of the horizontal force on top of the wall in function of the top horizontal displacement.

Fig.4 illustrates the crack propagation of wall 2. For the tested walls, quasi-diagonal cracks were generally observed. A horizontal crack, at the leftlower part of the wall, was also observed at an interface between two earthen layers. This horizontal crack appeared when the horizontal reached about 85% of the maximal load. The interfaces between earthen layers are usually considered as "weak points" for the RE walls, but the presented result shows that there is an acceptable cohesion between the earthen layers.



Fig. 4. Evolution of cracking for the wall 2 in function of the horizontal displacement.

Rocking of the walls at their base was noted for the tested walls but more clear for walls 2 and 3. These local uplifts were developed during the test, due to the more important tensile stresses of these walls which had a more important slenderness ratio.

### **IV Seismic assessment**

Two approaches are usually used to assess the seismic performance of a structure: the classical force-based approach and the more recent displacement-based approach [13]. The second approach is well-known more adapted for the earthquake design, that was why in this study, the displacement-based approach was used to assess the seismic performance of the studied walls.

First the demand spectrum has been built for the buildings of class II (current buildings), and for two types of foundation soil: type A and B. Following Eurocode 8, the A-type soil corresponds to a rock or very stiff soil (shear waves velocity  $v_s > 800$  m/s) and the B-type soil corresponds to a good soil (shear wave velocity  $v_s = 360-800$  m/s).



Fig.5. Capacity spectrum method for different zones of seismicity, case of soil A.

Volume No: 3 (2018), Issue No: 10 (October) www. IJRMS.com

October 2018



Fig. 5 presents the results for the type-A soil. The performance points for each wall on each seismicity zone can be determined (intersection points) which give the corresponding target displacements ( $S_d$  of the performance point). Then, the inter-story drift ratios of each wall can be calculated:

| Inter-story dr | ift = the target displac | cement / height |
|----------------|--------------------------|-----------------|
| of             | the                      | wall            |
| (2)            |                          |                 |

To assess the damage state from the drifts, the limits [14] for masonry structures were used (Fig. 6) because until now, no limit state (LS) has yet been proposed for RE walls. x LS1: no damage

x LS2 (Minor structural damage and/or moderate non-structural damage): structure can be utilized after the earthquake, without any need for significant strengthening and repair to structural elements. The suggested drift limit is 0.1 %.

x LS3 (Significant structural damage and extensive non-structural damage): the building cannot be used after the earthquake without significant repair. The suggested drift limit is 0.3 %.

x LS4 (Collapse): repairing the building is neither possible nor economically reasonable. The structure will have to be demolished after the earthquake. Beyond this LS, global collapse with danger for human life has to be expected. The suggested drift limit is 0.5 %.



### Fig. 7. Damage limit states following the drifts.

According to the above descriptions, LS3 can be considered as the limit for RE buildings. The LS of the studied walls for the type-A soil are summarized in Tab. 1. Following the used criteria, the studied walls can have a satisfactory performance on the seismicity zones from "very low" to "medium". The results for type-B soil are presented in Tab. 2, where the studied walls have an acceptable performance on the seismicity zones from "very low" to "moderate", except wall 1 which is acceptable only for "very low" and "moderate", due to its non-ductile behavior as mentioned earlier.

Table 1. Inter-story drifts calculated for soil A.

| Strong             |                            | Comp           | lete       |      | Complete               |              | Complete                  |              | Complete                  |
|--------------------|----------------------------|----------------|------------|------|------------------------|--------------|---------------------------|--------------|---------------------------|
|                    | 00                         | Moder          | ate        | 00   |                        |              |                           |              |                           |
| Medium             | 0.11<br>0.19               |                |            | 0.21 | Moderate               | 0.21<br>∞    | Moderate                  | 0.14<br>∞    | Moderate                  |
| Moderate           |                            | Moder<br>0.136 | ate        |      | Moderate               | 0.136        | Moderate                  | 0.064        | Slight                    |
| Low                | 0.056                      | Slight         | 0.059      |      | Slight                 | 0.059        | Slight                    | 0.035        | Slight                    |
| Very low           | 0.033                      | Slight         | 0.031      |      | Slight                 | 0.033        | Slight                    | 0.015        | Slight                    |
| Seismicity<br>zone | Wall I<br>Drift (<br>state | %)<br>Drift (' | Dama<br>%) | ge   | Wall 2<br>Damage state | Drift<br>(%) | Wall 3<br>Damage<br>state | Drift<br>(%) | Wall 4<br>Damage<br>state |
|                    | W-11 1                     |                |            |      | W-11 2                 |              | W-11.2                    |              | W7-11 4                   |



|                    | Wall  | 1 Drift (%) |              | Wall 2       |              | Wall 3          |              | Wall 4          |
|--------------------|-------|-------------|--------------|--------------|--------------|-----------------|--------------|-----------------|
| Seismicity<br>zone | Damaş | ge state    | Drift<br>(%) | Damage state | Drift<br>(%) | Damage<br>state | Drift<br>(%) | Damage<br>state |
| Very low           | 0.045 | Slight      | 0.045        | Slight       | 0.045        | Slight          | 0.023        | Slight          |
| Low                | 0.11  | Moderate    | 0.13         | Moderate     | 0.11         | Moderate        | 0.049        | Slight          |
| Moderate           | œ     | Complete    | 0.26         | Moderate     | 0.23         | Moderate        | 0.12         | Moderate        |
| Medium             | 00    | Complete    | 0.51         | Complete     | 0.5          | Extensive       | 0.41         | Extensive       |
| Strong             | œ     | Complete    | œ            | Complete     | 00           | Complete        | 00           | Complete        |

### Table 2. Inter-story drifts calculated f or soil B

### V. Conclusion and Outlook

This study investigates the in-plane seismic performance capacity of RE walls. Four walls with two different heights were constructed in laboratory and submitted to pushover tests. The capacity curves were established for the studied walls and the damage states were determined for different seismicity zones and soil types. Following the damage limits currently used for masonry structures, the studied RE walls can have a satisfactory performance on the seismicity zones from "very low" to "medium" with the type-A soil. However for type-B soil, the acceptable results were only found for seismicity zones from "very low" to "moderate" (except wall 1). Other soil types (C and D) were not studied but the performance would be less good than for the type-B soil. The different results obtained for walls 1 and 4 (with the same height) showed that the manufacturing process could have an important influence on the seismic performance of RE walls.

It is important to mention that the walls presented in this paper were tested under a vertical load of 120 kN (corresponding to the dead and live loads of the floor and roof), which is was an important load to support for a RE walls. This means the obtained results correspond to an unfavorable case in practice. For the case where these dead and live loads are less important (one story RE house; ground floor in RE and second floor in wood), the obtained seismic performance will be better.

The study used 0.5-scale RE walls for the pushover tests. A numerical model was performed with an advance FE code to simulate the experimental results on RE specimens [14]. Once the numerical model is validated by the pushover results presented in this paper, it can be used to investigate the seismic performance of the real scale RE walls. The scale effects will be then assessed.

This paper analyzes the numerical assessment of the effectiveness of a reinforcement technique adopting prestressed vertical steel rods on the maximum horizontal force of RE walls. The reinforcement technique consists of installing two vertical steel rods at two extremities of the wall. seismic The in-plane performance was investigated for the case of one-storey and twostorey walls. with three configurations: unreinforced RE wall, reinforced with vertical rods prestressed at 0.05 MPa, and reinforced with vertical rods prestressed at 0.10 MPa. The results showed that the reinforcement technique enhanced the elastic limit and the maximum horizontal force but also reduced the ductility of the RE walls. For the case of one-storey wall, the maximum horizontal force increased 22% and 27%. respectively, for the case of vertical rods prestressed at 0.05 and 0.10 MPa. The main damage observed was the failure in the compressive strut. Thus, it is expected that, with an RE material having a higher compressive strength, the robustness of this reinforcement technique can be improved.



ISSN No : 2455-7595 (Online)

International Journal of Research in

Management Studies

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