ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Seismic Assessment of Rammed Earth Walls

R Sathish
B. Tech Scholar
Department of Civil Engineering,
Siddhartha Institute of Engineering and Technology,
Vinobha Nagar, Ibrahimpatnam, Hyderabad,
Telangana 501506, India.

Ch Kusuma Keerthi
Assistant Professor
Department of Civil Engineering,
Siddhartha Institute of Engineering and Technology,
Vinobha Nagar, Ibrahimpatnam, Hyderabad,
Telangana 501506, India.

Abstract:

Rammed earth (RE) is attracting renewed interest throughout the world because of its low embodied energy and its interesting hygric-thermal behavior. Several studies have recently been carried out to investigate this material. However, the seismic behavior of RE walls is still an important subject that needs to be more thoroughly investigated. The present study assesses the seismic performance of RE walls by using the discrete element modeling (DEM) and the nonlinear pushover method. Firstly, nonlinear "force–displacement" 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). The results show that the studied walls can have satisfactory resistance in seismicity zones ranging from "very low" to "moderate" (according to Eurocode 8). For "medium" seismicity zones, the studied structures should only be constructed on A-type soils (very good soil). For B-type soils, wall reinforcement techniques would be necessary. Without special reinforcements, studied RE structures seem unsuitable for "strong" seismicity zones, for all soil types.

Subjects: ***Geomechanics; Soil Mechanics; Structural Engineering; Waste & Recycling***

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

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. Niroumand et al. [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. Venkatarama Reddy and Prasanna Kumar [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. Cheah et al. [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. Bouhicha et al. [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. Bui et al. [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 rammed earth buildings using various reinforcement technologies. Bu et al. [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.

Pushover method

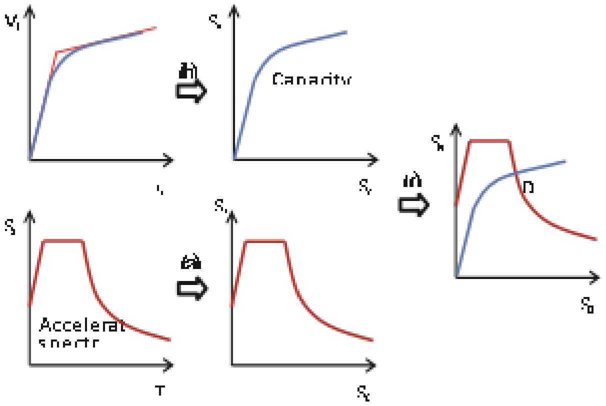

Fig. 1. Pushover analysis processing.

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:

$$S_d = \frac{T^2}{4\pi^2} S_a \qquad (1)$$

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

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 × 1.5 m width × 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 × 0.25 m × 1.8 m concrete beam. After the wall construction, another 0.25m × 0.25m × 1.8m 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 × 0.25m × 0.5 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 in Bui et al. [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 [12]. The moisture contents of all walls and specimens at the test moment were about 3 %.

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 ×1.5 m × 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.

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.

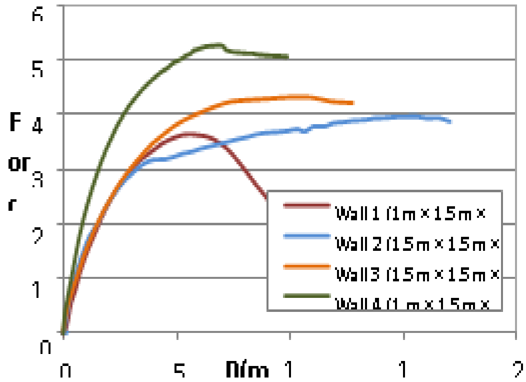

Fig. 3. The variation of the horizontal force on top of the wall in function of the top horizontal displacement.

Fig.4 illustrates the crack propagation of wall 2. For the tested walls, quasi-diagonal cracks were generally observed. A horizontal crack, at the left-lower 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.

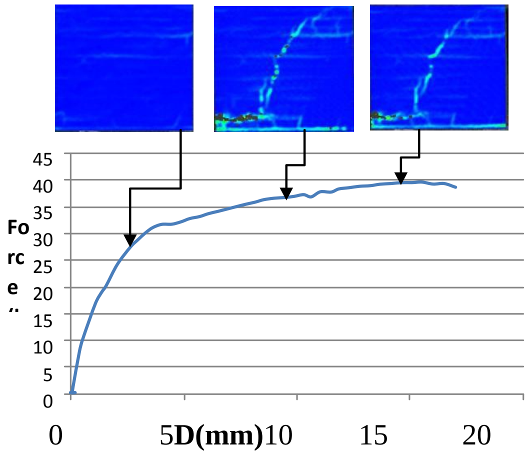

Fig. 4. Evolution of cracking for the wall 2 in function of the horizontal displacement.

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.

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).

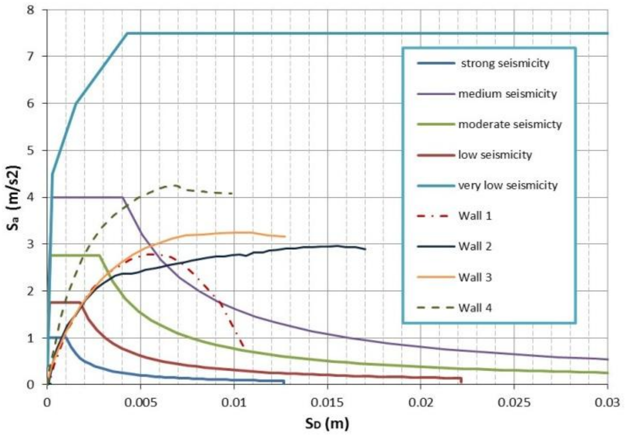

Fig.5. Capacity spectrum method for different zones of seismicity, case of soil A.

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 drift = the target displacement / height of the wall (2)

To assess the damage state from the drifts, the limits proposed by Calvi et al. [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 %.

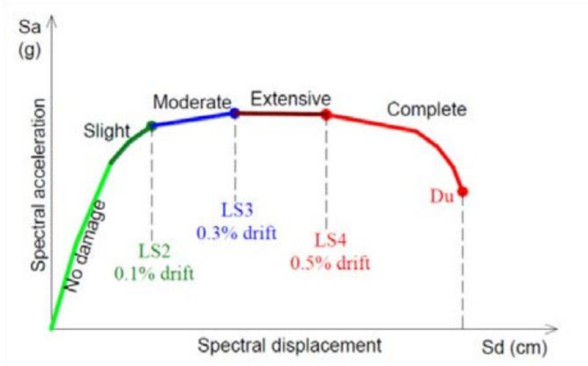

Fig. 7. Damage limit states following the drifts.

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.

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. The in-plane seismic performance was investigated for the case of one-storey and two-storey 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.

In the case of two-storey wall (with a height/length ratio of 2), the increase of the maximum force by using the reinforcement technique was in the range of 7–13% which was lower than that of the one-storey case. The main reason was that the main damage was inclined an angle about 45–50° which crossed the length of the wall, and there was not a diagonal damage. If a height/length ratio is like the case of one-storey wall (with a height/length ratio of 2), it is expected that the reinforcement techniques.

References

[1] R. Kumar, S. Sachdeva, and S. C. Kaushik, "Dynamic earthcontactbuilding: a sustainable low-energy technology,"Building and Environment, vol. 42, no. 6, pp. 2450–2460, 2007.

[2] M. I. Gomes, M. Lopes, and J. D. Brito, "Seismic resistance ofearth construction in Portugal," Engineering Structures,vol. 33, no. 3, pp. 932–941, 2011.

[3] H. Binici, O. Aksogan, and T. Shah, "Investigation of fiberreinforced mud brick as a building material," Constructionand Building Materials, vol. 19, no. 4, pp. 313–318, 2005.

[4] A. P. da Silva Milani and L. C. Labaki, "Physical, mechanical, and thermal performance of cement-stabilized rammedearth–rice husk ash walls," Journal of Materials in Civil Engineering,vol. 24, no. 6, pp. 775–782, 2012.

[5] B. V. Venkatarama Reddy and P. Prasanna Kumar, "Structuralbehavior of story-high cement-stabilized rammed-earth wallsunder compression," Journal of Materials in Civil Engineering,vol. 23, no. 3, pp. 240–247, 2011.

[6] H. Niroumand, M. F. M. Zain, and M. Jamil, "+e role ofnanotechnology in rammed earth walls and earth buildings,"Procedia—Social and Behavioral Sciences, vol. 89, pp. 243–247, 2013.

[7] B. V. Venkatarama Reddy and P. Prasanna Kumar, "Cementstabilised rammed earth. Part B: compressive strength andstress-strain characteristics," Materials and Structures, vol. 44, no. 3, pp. 695–707, 2011.

[8] J. S. J. Cheah, P. Walker, A. Heath, and T. K. K. B. Morgan,"Evaluating shear test methods for stabilised rammed earth,"Proceedings of the Institution of Civil Engineers-Construction Materials, vol. 165, no. 6, pp. 325–334, 2012.

[9] M. Bouhicha, F. Aouissi, and S. Kenai, "Performance ofcomposite soil reinforced with barley straw," Cement andConcrete Composites, vol. 27, no. 5, pp. 617–621, 2005.

[10] Q.-B. Bui, J.-C. Morel, S. Hans, and P. Walker, "Effect ofmoisture content on the mechanical characteristics of rammedearth," Construction and Building Materials, vol. 54, no. 15,pp. 163–169, 2014.

[11] Y.-H. Bu, Y.-H. Wang, G. Han, and L. Li, "Experimental studyon seismic behavior of raw-soil structure with rammed earthwalls by different construction methods," Journal of Chang'anUniversity, vol. 31, no. 6, pp. 72–76, 2011.

[12] A.K. Chopra, R.K. Goel, A modal pushover analysis procedure for estimating seismic demands for buildings, Earthquake Engineering & Structural Dynamics, 31 (2002) 561-582.

[13] G.M. Calvi, A displacement-based approach for vulnerability evaluation of classes of buildings. Journal of Earthquake Engineering, 3 (1999) 411-38.

[14] R. Nabouch, Q.B. Bui, P. Perrotin, O. Plé, J.P. Plassiard, Numerical modeling of rammed earth constructions: analysis and recommendations, 1st International Conference on Bio-based Building Materials, Clermont Ferrand (France), RILEM, June 21-24 2015, paper 57.