www.czasopisma.pan.pl PAN www.journals.pan.pl

WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.140645

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 2 2022

pp. 325 – 335

Research paper

Probabilistic assessment of the seismic vulnerability of a rammed earth construction: a case study

Balil Jama[1], Driss Agliz[2], Atmani Abderrahman[3], Mina Derife[4]

Abstract: Rammed earth significantly reduces intrinsic energy compared to concrete construction and has an environmental benefit throughout the life cycle of the building: phases of construction, operation, maintenance, renovation, and demolition. Several studies have recently been carried out to study this material. However, the seismic behavior of rammed earth constructions is still an important topic that needs to be studied in more detail. Through the analysis of non-linear behavior of the rammed earth construction for different wall thicknesses according to the Moroccan earthquake regulation RPS2011, we were able to assess the seismic performance under the corresponding conditions (loads, seismic zone). The results show that the walls studied can have good resistance in areas of seismicity ranging from "very low" to "moderate" and acceptable performance in areas of high seismicity. Furthermore, fragility analysis shows that rammed construction with a wall thickness equal to 50 centimeters exhibits better seismic performance and a low probability of damage, particularly in the case of moderate, severe, and complete damage states.

Keywords: rammed earth, vulnerability, probability, capacity curve, earthquake

[1]PhD., Eng., Laboratory of Energy Engineering, Materials and Systems (LGEMS), National School of Applied Sciences, Ibn Zohr University, Agadir, Morocco, e-mail: j.balil@nextetudes.com, ORCID: 0000-0002-0790-389X
[2]Prof., PhD., Laboratory of Energy Engineering, Materials and Systems (LGEMS), National School of Applied Sciences, Ibn Zohr University, Agadir, Morocco, e-mail: d.agliz@uiz.ac.ma, ORCID: 0000-0002-0367-2537
[3]Prof., PhD., Laboratory of Energy Engineering, Materials and Systems (LGEMS), National School of Applied Sciences, Ibn Zohr University, Agadir, Morocco, e-mail: a.atmani@uiz.ac.ma, ORCID: 0000-0001-9892-6220
[4]PhD., Eng., Laboratory of Energy Engineering, Materials and Systems (LGEMS), National School of Applied Sciences, Ibn Zohr University, Agadir, Morocco, e-mail: mina.derife@edu.uiz.ac.ma, ORCID: 0000-0003-1127-7753

1. Introduction

Rammed earth buildings have an important cultural value and correspond to a heritage that must be preserved for future generations. Around the world, rammed earth buildings use soil as a structural material [1–3]. Rammed earth constructions dominated Morocco until the last quarter of the 20th century. The method of execution of rammed earth walls involves mixing the earth with hay and water. This mixture is then compacted using vertical formwork (made of wood or metal). The rammed earth is compacted in layers of about 15 cm using a manual or pneumatic pestle. The "rammed earth" material works mainly in compression and has a very low tensile strength [4]. The heavy mass of walls can lead to considerable inertial forces during earthquakes. There are several examples of recent earthquakes that have severely affected earthen constructions, showing the vulnerability of this type of building, such as El Salvador earthquake in 2001, Iran earthquake in 2003 and Peru earthquake in 2007 [5]. However, according to the Darfield Earthquake Survey (2010, New Zealand, 7.1 on the Richter magnitude scale) [6], only minor cracks were observed in the earthen walls. This indicates that when rammed earth buildings are well designed and executed, they can have acceptable seismic performance [7].

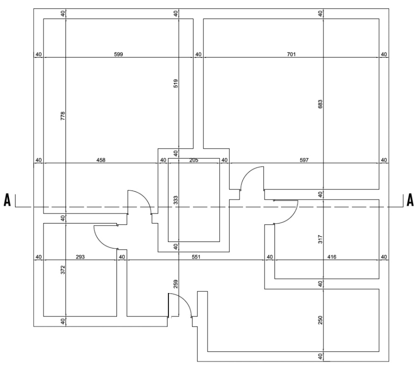
Indeed, rammed earth structures continue to be used in zones of different seismic intensities, which shows the immediate need to develop means to improve the seismic behavior of these structures. Indeed, there is a need for research studies on performance and retrofit improvement solutions. In this regard, Roberto P. et al. [8] studied the seismic vulnerability of rammed earth construction. The researchers showed that traditional construction practices could influence the seismic failure mechanisms of this type of structure. Also, Arto I. et al. [9] studied the seismic vulnerability of medieval earthen fortifications in southeastern Spain. A sensitivity analysis to know the influence of the construction technique, the material condition, and the typology of the structure on the value of the damage grade was performed. The researchers reported that rammed earth structures require special attention to improve their seismic performance. Furthermore, N. Chettri et al. [10] conducted a study on the seismic vulnerability of Bhutanese vernacular constructions based on the damage caused by the earthquakes in 2009 and 2011. Interpretations of the damage and seismic vulnerability characteristics of these constructions are provided based on field observations. Empirical seismic fragility functions for vernacular rammed earth buildings are constructed using the damage data from the 2009 and 2011 earthquakes. The results of the observations highlight that rammed earth buildings are highly vulnerable even during moderate earthquakes. Moreover, Juan C. Reyes et al. [11] investigated the shear behavior of adobe and rammed earth walls in heritage structures. The researchers concluded that the failure mechanisms of earthen walls are characterized by the presence of diagonal cracks that divide the walls into large segments that eventually detach, resulting in a loss of shear capacity.

However, despite all the studies reported in this sense, the behavior of the rammed earth structures under seismic solicitations must be thoroughly investigated to better understand the failure mechanisms of this type of structure. Therefore, the primary purpose of this research work is to study quantitatively the seismic performance of rammed earth construction, taking into account parameters such as seismic action (seismic zone, type of soil, site factors) according to RPS2011 [12], dynamic characteristics of the structure (natural frequencies, modal forms, damping) and material characteristics (compressive strength, tensile strength, Young's modulus, density) according to RPCT2011 [13]. Then, nonlinear static analyses [14] were conducted to study the influence of wall thickness on seismic vulnerability, considering three models with wall thicknesses of 40, 50, and 60 cm.

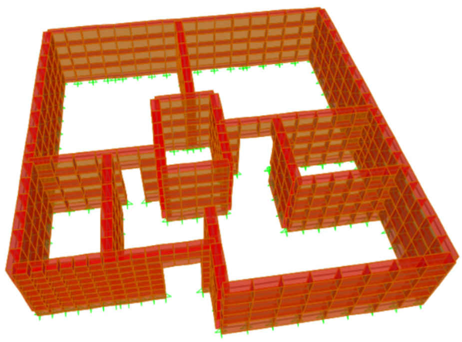
2. Dynamic approach

2.1. Studied structure

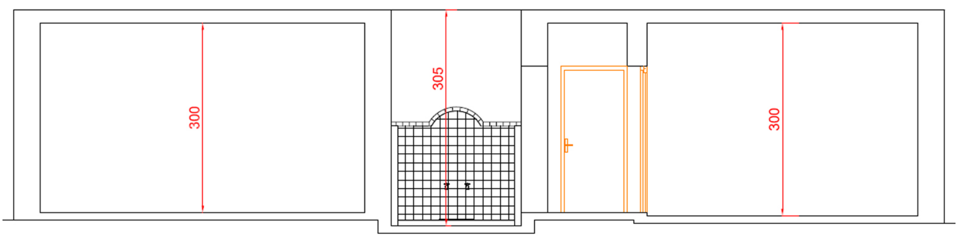
The typical construction studied, Figure 1, is located in the TATA (TAGNART) region of Morocco with an acceleration of 0.04 g [12]. The bracing system adopted in this structure is of the multi-thickness rammed earth load-bearing wall type of 40 cm for variant A, 50 cm for variant B, and 60 cm for variant C. For this purpose, the soil is compacted between forms called wooden benches. The compaction is implemented in successive layers of 20 cm by means of a traditional tamper. In This study, the material is assumed to be isotropic. The foundation adopted for the construction is of the rammed earth type, with a depth of 60 centimeters.



(a) Ground plan



(b) 3D view



(c) Section A–A

Fig. 1. Model of the rammed earth construction

The construction's dimensions are 14.60 m in length, 14.50 m in width, and 3.00 m in height. The upper roof of the structure is made up of main beams in cedar wood with a diameter of 30 cm with an inter-distance of 2 m, distribution beams in oak wood with a diameter of 10 cm with an inter-distance of 1 m, a reed panel, film in plastic and a layer of rammed earth 20 cm thick. The data necessary to conduct this study are collected in Table 1.

Table 1. Mechanical characteristics of rammed earth [12, 15, 16]

Parameters	Value
Compression resistance (MPa)	2.46
Young's modulus (MPa)	160
Soil type	very dense soil (S2)
Damping coefficient (%)	3.17
Priority coefficient	1
Poisson coefficient	0.22

2.2. Seismic performance

The structure's seismic performance can be assessed using several approaches [7]. In this research study, the seismic response of rammed earth building is assessed using non-linear static (Pushover) analysis [17]. This evaluation consists in applying to the upper roof of the construction a force Fi, horizontal static monotonic progressive, corresponding to the force of inertia at the same point due to an acceleration of the ground (a_i).

The gradual increase in Fi increases displacement (δ_i) of the top roof of the construction and the shear stress V_{bi} at the base until the structure collapses. By superimposing in the same diagram (S_a; S_δ) the capacity spectrum and the demand spectrum, we determine the performance point δ_p [18] characterizing the intersection between the two curves, as shown in Figure 2.

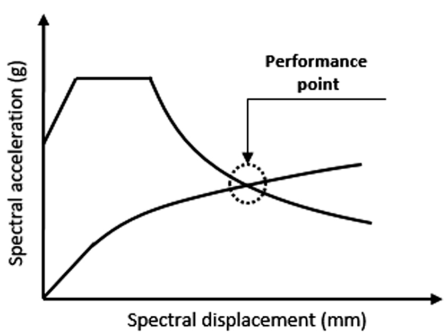


Fig. 2. Performance point computation [19]

This performance point [18] makes it possible, on the one hand, to determine the nature of the seismic behavior of the structure, elastic or plastic, and on the other hand, to apprehend the states of damage to the structure and to analyze the impact of thicknesses in this seismic evaluation.

The transition from the capacity curve $(F; \delta)$ to the capacity spectrum $(S_a; S_\delta)$ is done through a mathematical transformation [19]:

$$S_a = \frac{V_b}{m} \tag{2.1}$$

where: m – the mass of the construction, V_b – base shear, S_a – spectral acceleration.

$$S_\delta = \frac{T^2}{4\pi^2} S_a \tag{2.2}$$

where: δ – the displacement of the top of the wall, S_δ – spectral displacement. T – the period of the building.

3. Vulnerability assessment

The probability distribution model considered for the present study is log-normal [20], defined by two important parameters, the mean spectral displacement $S_{\delta,ds}$, and the standard deviation β_{ds}. For a given state of damage ds, the curve of brittleness is given by [21]:

$$P(ds, Sd) = \Phi \left[\frac{1}{\beta_{ds}} \ln \left(\frac{Sd}{S_{\delta,ds}} \right) \right] \tag{3.1}$$

where: Φ stands for the cumulative normal distribution, $S_{\delta,ds}$ is the average value of displacement δ for the level of damage ds, and β_{ds} represents the standard deviation of the displacement for the level of damage ds.

To evaluate the damage state of the rammed earth construction, we have retained the limit states [22] in Figure 3 and Table 2.

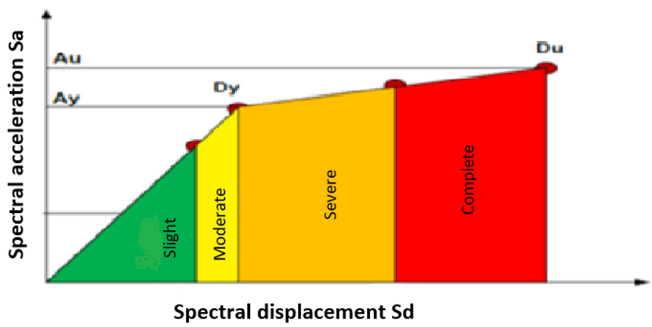


Fig. 3. Limit states of damage due to displacement [17], where: A_u and A_y correspond respectively to the accelerations of the ultimate and elastic limit states. D_u and D_y correspond respectively to displacements of the ultimate and elastic limit states

Table 2. Limitations of damage

Limit state	Description	(*) Differential inter-storey displacement Δ
LS1	No damage	0 to 0.1%
LS2	Minor structural damage and/or moderate non-structural damage	0.1% to 0.3%
LS3	Significant structural damage and significant non-structural damage	0.3% to 0.5%
LS4	Collapse	More than 0.5%

With: (*) Differential inter-storey displacement: $\Delta = \frac{S_\delta}{h}$; ($S_\delta$ is the displacement of the roof at the performance point and h is the height of the construction).

4. Results and discussions

4.1. Capacity curve evaluation

A determination of the capacity curves [18] allowed us to define the intrinsic behavior of the rammed earth material under seismic stress, and this is through the integration of the nonlinear static evaluation strategy [17]. From the capacity curves, we can determine the damage limits for the studied rammed earth construction.

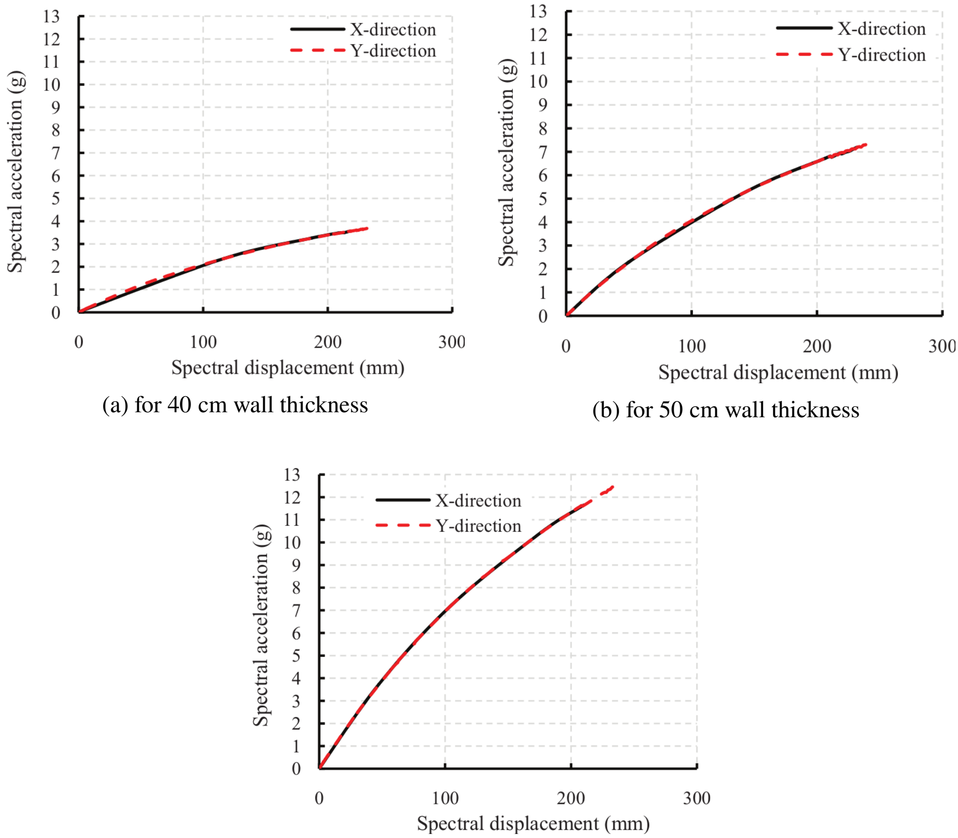
Figure 4 shows the results and performance points that were found for the three 40 cm, 50 cm, and 60 cm thick constructions.

From Figure 4, it can be seen that despite the change in thickness of the walls of the construction, the performance point for the three types of construction is in the elastic zone of their capacity curves. This proves that the thickness of the walls does not influence the elastic behavior of the rammed earth construction. As well as, no repair will be requested to rehabilitate the construction after an earthquake with an acceleration lower than that corresponding to the performance point δ_p. It is also noted that for these points, δ_p a weak displacement of around 0.6 cm, which proves that the rammed earth construction does not withstand large displacements.

4.2. Probabilistic assessment

The approach taken into account for the evaluation of the damage probabilities is based on the determination of the fragility curves using the HAZUS method [23]. Knowing the maximum displacement suffered by a type of building, we deduce the probability of reaching or exceeding four damage levels. Figures 5 and 6 show the fragility curves obtained in this study for a seismic action in both X and Y directions.

The probabilistic evaluation of the rammed earth construction has shown us, for all the thicknesses, that the damage to the structure is of secondary order or even negligible in



(a) for 40 cm wall thickness

(b) for 50 cm wall thickness

(c) for 60 cm wall thickness

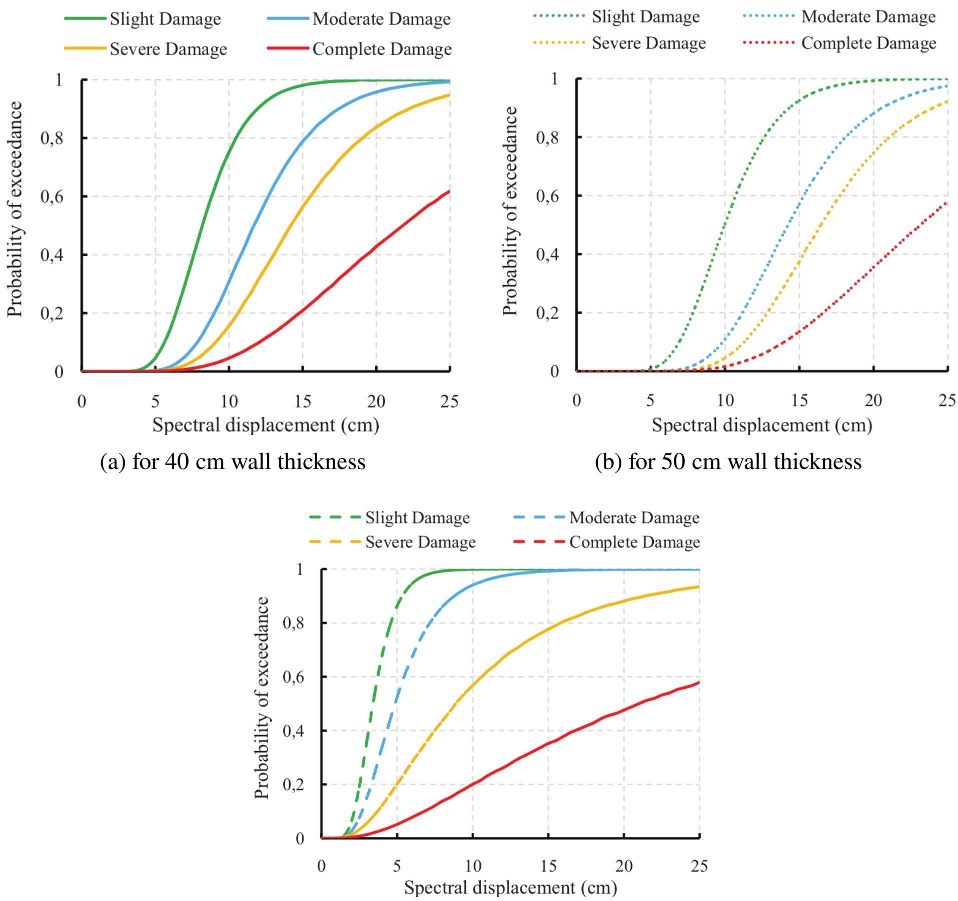
Fig. 4. Capacity curves for construction model with different wall thicknesses

areas of low and medium seismicity. Table 3 summarizes the evaluation carried out on the construction variants according to the limit states proposed by [23].

Table 3. Damage assessment (displacement ratio)

	None	Slight	Moderate	Severe	Complete
Wall_40	0.2483	0.4432	0.1523	0.1107	0.0455
Wall_50	0.496	0.3947	0.0638	0.0293	0.0162
Wall_60	0.0011	0.0583	0.3731	0.3670	0.2005

From the analysis of the probabilistic evaluation results of the rammed earth construction as illustrated in Figure 7, for the zone of low seismicity [12] (acceleration coefficient



(a) for 40 cm wall thickness

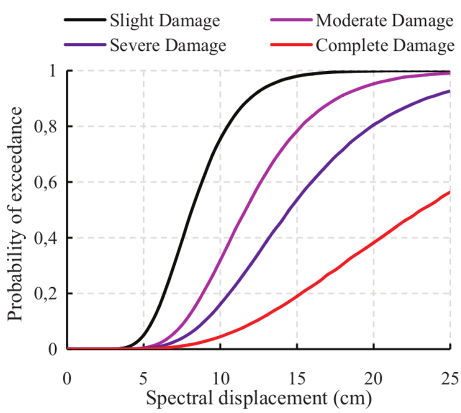
(b) for 50 cm wall thickness

(c) for 60 cm wall thickness

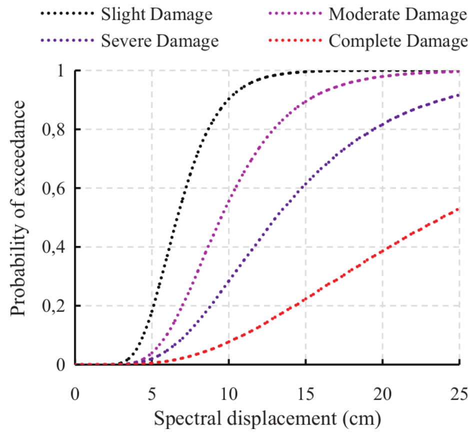
Fig. 5. Fragility curves of the studied constructions for a seismic action in the X–X direction

less than 0.07 g), it can be concluded that the stability of the structure subjected to displacement, at the high point of the structure, we have three stability scenarios:

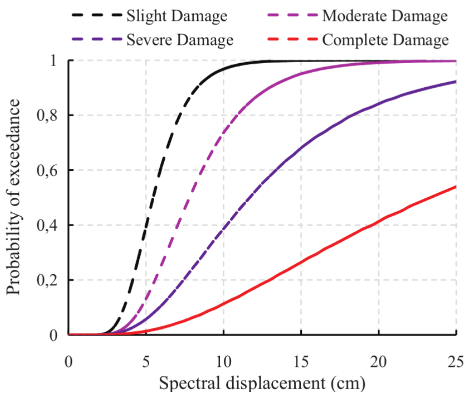
1. For a displacement less than 2 cm, the stability of the structure is efficient for the three types of thickness: the probability of damage is negligible, corresponding to the elastic behavior of the structure. The structure will therefore undergo a state of superficial damage (or of no damage).
2. For a displacement between 2 cm and 4 cm, the stability of the structure is not in danger: the damage corresponds to a controlled level of damage, but slight damage is likely to develop.
3. A displacement beyond 4 cm, the stability of the structure is in danger: the damage corresponds to an advanced level. Beyond this level, the structure is susceptible to collapse.



(a) for 40 cm wall thickness



(b) for 50 cm wall thickness



(c) for 60 cm wall thickness

Fig. 6. Fragility curves of the studied constructions for a seismic action in the Y-Y direction

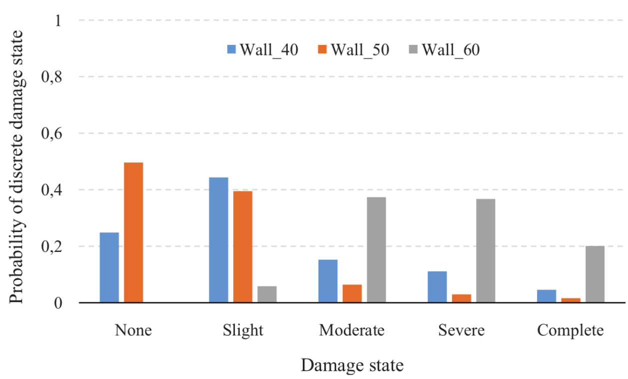


Fig. 7. Probability of damage for a displacement of 10 cm

5. Conclusions

In this work, the dynamic behavior of a rammed earth construction was evaluated through spectral evaluation and probabilistic damage evaluation.

Unlike reinforced concrete, rammed earth construction is known for its thick, heavy walls and light, flexible floors, the classical method of concentrated masses is not suitable for this material. So we opted for the probabilistic approach to study the impact of the thickness of the exterior walls on the dynamic behavior of the rammed earth construction.

The result of the study is summarized in the fact that, for the zone of low seismicity (acceleration less than 0.07 g) [12], the structure will have performance stability for any wall thickness. This study can be a basis for other similar studies on different types of construction, taking their environmental and regulatory context, to confirm and generalize this result.

References

[1] H. Araki, J. Koseki, T. Sato, "Tensile strength of compacted rammed earth materials", *Soils and Foundations*, 2016, vol. 56, no. 2, pp. 189–204, DOI: 10.1016/j.sandf.2016.02.003.

[2] M.I. Gomes, M. Lopes, J. De Brito, "Seismic resistance of earth construction in Portugal", *Engineering Structures*, 2011, vol. 33, no. 3, pp. 932–941, DOI: 10.1016/j.engstruct.2010.12.014.

[3] R. Illampas, D.C. Charmpis, I. Ioannou, "Laboratory testing and finite element simulation of the structural response of an adobe masonry building under horizontal loading", *Engineering Structures*, 2014, vol. 80, pp. 362–376, DOI: 10.1016/j.engstruct.2014.09.008.

[4] Q.B. Bui, et al., "Compression behaviour of non-industrial materials in civil engineering by three scale experiments: the case of rammed earth", *Materials and structures*, 2009, vol. 42, no. 8, pp. 1101–1116, DOI: 10.1617/s11527-008-9446-y.

[5] C.F. Oliveira, H. Varum, J. Vargas, "Earthen Construction: Structural Vulnerabilities and Retrofit Solutions for Seismic Actions", in *15th World Conference on Earthquake Engineering*, Lisbon, 2012.

[6] H. Morris, "Seismic Research on Earth Building related to the 1998 New Zealand Earth Building Standards", New Zealand, 2005. [Online]. Available: https://buildwellsource.org/materials/materials-natural-rural/earth/141-seismic-research-on-earth-building-related-to-the-1998-new-zealand-earth-building-standards-hugh-morris-2005.

[7] T.T. Bui, et al., "Failure of rammed earth walls: from observations to quantifications", *Construction and Building Materials*, 2014, vol. 51, pp. 295–302, DOI: 10.1016/j.conbuildmat.2013.10.053.

[8] R. Pennacchio, et al., "Influence of Traditional Building Practices in Seismic Vulnerability of Bhutanese Vernacular Rammed Earth Architecture", *International Journal of Architectural Heritage*, 2020, DOI: 10.1080/ 15583058.2020.1785044.

[9] I. Arto, J. Garrido, M.L. Gutiérrez-Carrillo, "Seismic vulnerability analysis of medieval rammed earth fortifications in southeastern Spain", *Bulletin of Earthquake Engineering,* 2020, vol. 18, pp. 5827–5858, DOI: 10.1007/s10518-020-00912-1.

[10] N. Chettri, D. Gautam, R. Rupakhety, "Seismic Vulnerability of Vernacular Residential Buildings in Bhutan", *Journal of Earthquake Engineering*, 2021, pp. 1–16, DOI: 10.1080/13632469.2020.1868362.

[11] J.C. Reyes, et al., "Shear behavior of adobe and rammed earth walls of heritage structures", *Engineering structures*, 2018, vol. 174, pp. 526–537, DOI: 10.1016/j.engstruct.2018.07.061.

[12] RPS2011, *Moroccan seismic regulations*. Ministry of Housing and Spatial Planning, Morocco, 2011.

[13] RPCT, *Earthquake Regulations for Earthen Buildings*. National Committee for Earthen Buildings, Morocco, 2013.

[14] A.K. Chopra, R.K. Goel, *A Modal Pushover Analysis Procedure to Estimating Seismic Demands for Buildings: Theory and Preliminary Evaluation*. PEER Report 2001/03, Pacific Earthquake Engineering Research Center, University of California, Berkeley, 2001.

[15] V. Maniatidis, P. Walker, "Structural Capacity of Rammed Earth in Compression", *Journal of Materials in Civil Engineering*, 2008, vol. 20, no. 3, pp. 230-238, DOI: 10.1061/(ASCE)0899-1561(2008)20:3(230).

[16] J. Balil, A. Atmani, D. Agliz, "Parametric Study of Response Spectrum of Rammed Earth Construction in Morocco", *International Journal of Civil Engineering and Technology*, 2020, vol. 11, no. 7, pp. 21–28, DOI: 10.34218/IJCIET.11.7.2020.003.

[17] FEMA P-58-1, *Seismic performance assessment of buildings-Methodology*. Applied Technology Council, Washington DC, USA, 2012.

[18] ATC-40, *Seismic Evaluation and Retrofit of Concrete Buildings*. Vol. 1. Applied Technology Council, Redwood City, California, 1996.

[19] P. Fajfar, "A nonlinear analysis method for performance based seismic design", *Earthquake Spectra*, 2000, vol. 16, pp. 573–592, DOI: 10.1193/1.1586128.

[20] RISK-UE, *An advanced approach to earthquake risk scenarios with applications to different European towns*. WP4: Vulnerability of current buildings, European Project, 2003.

[21] M. Shinozuka, et al., "Nonlinear static procedure for fragility curve development", *Journal of Engineering Mechanics*, 2000, vol. 126, no. 12, pp. 1287–1295, DOI: 10.1061/(ASCE)0733-9399(2000)126:12(1287).

[22] G. Calvi, et al., "Development of seismic vulnerability assessment methodologies over the past 30 years", *ISET Journal of Earthquake Technology*, 2006, vol. 43, no. 3, pp. 75–104.

[23] HAZUS-MH MR1, *Earthquake Loss Estimation Methodology*. National Institute of Building Sciences for the Federal Emergency Management Agency, Washington, D.C., 2000.

Received: 21.01.2022, Revised: 08.02.2022