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# Assessing the in-plane seismic performance of rammed earth walls by using horizontal loading tests

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ABSTRACT

Rammed earth (RE) construction is attracting renewed interest throughout the world thanks to its sustainable characteristics: very low embodied energy, advantageous living comfort due to substantial thermal inertia, good natural moisture buffering and an attractive appearance. This is why several studies have recently been conducted to investigate RE. However, there have not yet been sufficient studies on the seismic performance of RE buildings. This paper presents an experimental study on the static nonlinear pushover method and its application to the seismic performance of RE structures. Several walls with different height/length ratios were built and tested to obtain nonlinear shear force–displacement curves. By transposing these shear force-displacement curves to an acceleration–displacement system and using the standard spectra presented in Eurocode 8, the performance points were determined, making it possible to assess the seismic performance of the walls studied in different conditions (seismicity zones and soil types).



## 1. Introduction

One of the most common materials used in the past is rammed earth (RE). With other forms of local earthen construction, RE has a long and continuous history in many regions throughout the world. Due to a low embodied energy and an interesting hygrothermal behaviour, RE constructions have become competitive when compared to conventional materials [1].

RE walls are made by compacting earth between vertical formworks (wooden or metal panels). The earth is compacted into layers approximately 15 cm thick using a manual or pneumatic rammer. Today, the pneumatic rammer is more currently used.

In the context of sustainable development and preserving the heritage of RE buildings, several studies have recently been conducted to investigate several aspects of this material: durability [2], mechanical characteristics [3–5] and thermal behaviour [6,7]. However, there have been few studies on the seismic performance of RE buildings. Among the studies on the seismic aspects, Bui et al. [8] determined the dynamic characteristics of RE buildings (natural frequencies, mode shapes, and damping) which were important to calculate the seismic loading applied on RE buildings. These authors also showed that RE houses had mainly a shear behaviour in dynamic and the first natural frequency was predominant. Gomes et al. [9] investigated the seismic resistance of earth constructions in Portugal by using a numerical modelling which based on simplified models (linear-elastic behaviour). So, the seismic performance of RE still needs to be studied more thoroughly. This paper presents an investigation which assesses the seismic performance of RE walls by using the non-linear behaviour obtained from experiments. A robust theoretical approach (pushover method) proposed in standards was employed in the present paper for the seismic assessment.

## 2. Pushover method

The pushover test is a nonlinear static method which uses the displacement-based approach and is currently applied to assess the seismic performance of structures [10,11]. This method was introduced in several standards, for example Eurocode 8 [10]. The processing is summarised in Fig. 1 where the studied structure is converted to an equivalent single degree of freedom system. First, the standard acceleration spectrum $S_e$ is transformed into an acceleration–displacement ($S_e$-$S_D$) format (Fig. 1a), where $S_D$ is the response spectrum in displacement, expressed as:

$$S_D = \frac{T^2}{4\pi^2} S_e \quad (1)$$

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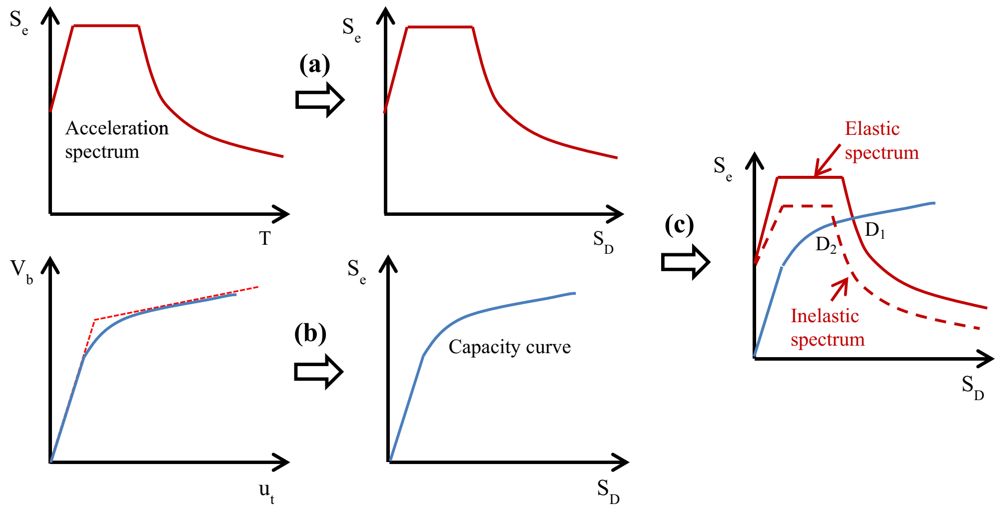


**Fig. 1.** Pushover analysis processing.

The capacity curve – presented by the relationship between the base shear force $V_b$ and roof displacement $u_t$ (Fig. 1b) – is also established in ($S_e$-$S_D$) format where the shear force $V_b$ is converted to the maximum acceleration $S_e$, by the relationship $S_e = V_b/m$, with $m$ is the mass of the equivalent single degree of freedom system; and the displacement on top of the wall is equal to spectral displacement $S_D$ (Fig. 1b).

The intersection point $D_1$ between the capacity curve and the demand spectrum (Fig. 1c) is called the performance point. From the performance point, the seismic performance of the studied structure can be assessed. This method is efficient when the first mode is predominant [10,11], which is the case of RE constructions [8].

The pushover method is a nonlinear analysis which recognizes that inelastic deformation should be taken into account. In general, the design (inelastic) spectrum can be obtained by dividing the elastic spectrum by a "behaviour factor" $q$. This is an important parameter which implicitly accounts the inelastic response, the presence of damping and other force reducing effects, such as soil-structure interaction. The behaviour factor is defined as the ratio of the elastic acceleration response spectrum ($S_e$) expected at a site to that of an inelastic spectrum used for the design of a structure [12]. There has not yet been a specific value of $q$ for RE structures, but for unreinforced masonry structures, Eurocode 8 authorizes that $q$ is taken to be at least 1.5. If the inelastic spectrum is used, the performance point will be $D_2$ (Fig. 1c).

## 3. Experiments

### 3.1. Earth used

The earth used was provided by a professional RE builder, in the Rhone-Alpes region (France). The grain size distribution of the earth is presented in Fig. 2. The clay content in the soil used was approximately 19%.

### 3.2. Specimen manufacturing

RE walls were constructed in the laboratory, with two different height/width ratios. Two walls were 1.5-m-high × 1.5-m-wide × 0.25-m-thick, representing at the 0.5-scale a 3-m-high × 3-m-wide × 0.5-m-thick wall, which is the current configuration of RE walls in France. Two other walls had the same width and thickness but were 1.0 m high, to study the influence of the height/width ratio on the in-plane seismic performance of RE walls.

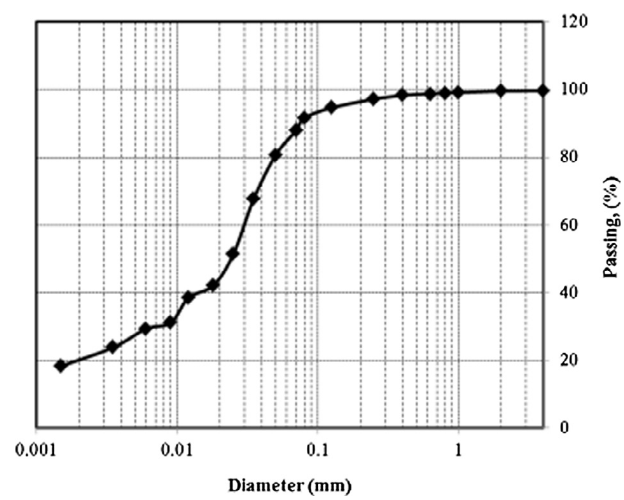


**Fig. 2.** Grain size distribution of the earth used.

Water was added to the earth to obtain the optimum manufacturing water content [3], approximately 12% by weight in this case. The mixture was then poured into a formwork and compacted in layers using a pneumatic rammer. The wall was built on a 0.25-m × 0.25-m × 1.8-m concrete beam (Fig. 3). The walls were unmoulded from their formwork after the manufacturing and then were cured at laboratory ambient conditions (20 °C and 60% relative humidity, RH) for 2 months. This is the time necessary to obtain quasi-dry specimens [3]. The moisture content of the walls after 2 months were about 3% (determined after the pushover tests). After the wall was erected, another 0.25-m × 0.25-m × 1.8-m concrete beam was placed on top of the wall (Fig. 3). This beam made it possible to apply a horizontal load on the top of the wall during the pushover test. Before installing 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.

To determine the compressive strength and the Young modulus of the earth used for the walls, cylindrical and prismatic specimens were also manufactured. The cylindrical specimens had a 0.2-m diameter and 0.4-m height and the prismatic specimens measured 0.25 m × 0.25 m × 0.50 m. The dimensions of these specimens