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Dynamic discrete element modelling for seismic assessment of rammed earth walls

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ABSTRACT

Rammed earth (RE) is a construction material which is manufactured by compacting the soil within a formwork, in superimposed layers. RE is attracting scientific studies because of its sustainable properties : a very low embodied energy and an advantageous living comfort due to a particular benefic hygro-thermal behaviour. Numerous studies have been conducted to investigate RE material and RE structures, however, a lack of knowledge on the seismic performance of RE buildings is noticed. This paper presents an advanced numerical study to investigate the in-plane seismic behaviour of RE walls. First, a numerical model of an in-situ RE wall was constructed by using discrete element modelling (DEM). The relevancy of the numerical model was verified by comparing dynamic properties of the model with that measured on the in-situ wall. Then, a real earthquake excitation was applied to the model, in order to evaluate the seismic performance of the RE wall studied. This is the first time, to our knowledge, that a dynamic discrete explicite analysis was performed for a RE wall. The excitation was scaled at different amplitudes to assess the damages following different earthquake intensities. The results showed that for seismic excitations lower than 2.3 m/s^2, RE walls studied had satisfying in-plane earthquake performance.

1. Introduction

Rammed earth (RE) is a construction material which is manufactured by compacting the soil in formworks, in successive layers [1]. The thickness of each compacted earthen layer is about 10–15 cm (Fig. 1) [1]. The interfaces between earthen layers are usually considered as weak points of RE wall under horizontal loadings, thus in several cases, some thin horizontal lime layers are added to improve the cohesion between earthen layer (white horizontal lines in Fig. 1: one thin lime layer for 3–5 RE layers). RE can be used without added binders (unstabilized RE) or with added binders (cement, lime or geopolymer [2,3]), that is called stabilized RE.

Rammed earth is attracting attentions in the context of sustainable development because of its low embodied energy and its interesting hygric-thermal behavior [4,5]. Several studies have been conducted to investigate this material, on different aspects: durability, mechanical characteristics, hygro-thermal behaviour [6–13]; however, the seismic behavior of RE walls still requires more thorough investigations. The first exploratory study on the dynamic characteristics of RE buildings was carried out by Bui et al. [14], in which the dynamic characteristics (natural frequencies, mode shapes and the damping) of the studied RE buildings were identified. This study also showed that the dynamic behavior of RE buildings was more likely a shear-beam model than a concentrated mass model, which is currently used in engineering practices.

Gomes et al. [15] conducted a numerical study on the seismic resistance of RE constructions in Portugal, but the behavior of RE material was not analyzed in detail, no validation step was performed for the numerical model, and the seismic assessment was conducted by using the classical spectral analysis, which was less realistic than the nonlinear approaches because the damage apparition and progression was not considered.

Cheah et al. [16], Hamilton et al. [17], Miccoli et al. [18], and Silva et al. [19] present various experiments on the shear behavior of several RE walls (stabilized or unstabilized, unreinforced or reinforced); Ciancio & Augarde [20] studied the out-of-plane behaviour of stabilized RE subject to lateral wind force. However, to our knowledge, there has not yet been any quantitative study on the seismic performance of RE buildings at the structure scale.

Recently, Bui et al. [21], El-Nabouch et al. [22] have applied the

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Fig. 1. Example of a RE wall using thin lime layers in France. Source: TERA.

pushover method to assess the in-plane earthquake performance of RE walls. The first study used a numerical approach while the second one used experimental tests. The results obtained with the pushover method are interesting because this is a robust nonlinear method. However the pushover method remains a static method in which the dynamic effects are not directly taken into account. To thoroughly investigate the dynamic effects, a time history analysis study is necessary. The aim of this paper is to investigate the in-plane earthquake performance of RE walls by using the time history analysis with a real earthquake signal and the model is performed by using the discrete element method.

2. Approach adopted

This paper investigates two current types of RE buildings in France and Europe: 1-storey and 2-storeys in RE walls. The RE walls are 50-cm-thick unstabilized RE, built by a pneumatic rammer and their seismic performance is investigated for an almost dry state, several months after their construction (about 2–3% of moisture content [9,10]). The influences of the moisture content variation on the earthquake performance is not considered in the present paper.

From the point of view of seismic design, the horizontal loadings should be supported only by the in-plane resistance of load-bearing-walls, the out-of-plane resistance of the perpendicular walls should be neglected in the design of the whole structure, which is in the safe side. Therefore, the in-plane seismic performance should be correctly designed and executed to resist the total horizontal load. The out-of-plane seismic performance should be verified for each wall (not for whole structure resistance) which is not investigated in this paper.

It is also important to note that the seismic behavior of a RE building depends on several parameters: earthquake action (seismicity zone, soil type, site factors), the structure's dynamic characteristics (natural frequencies, modal shapes, damping), the material's characteristics (compressive, tensile strengths, Young's modulus, density) and the structural typology (spans' length, links with other structural and non-structural elements). This is why for the same material (RE in this case), the seismic performance of each building may differ depending on its structural characteristics and the quality of its execution. Thus, the earthquake performance of each building should be studied case by case by structural engineers. However, the methods used by the engineers are usually simplified and their relevancy for RE structures have not yet been investigated. The approach adopted of the present study is to use the advanced methods which are the discrete modelling (DEM), the time history analysis and the incremental dynamic analysis (IDA) [23] to provide the most general response possible for the question about the earthquake performance of RE buildings, which is one of the very important topic in this field.

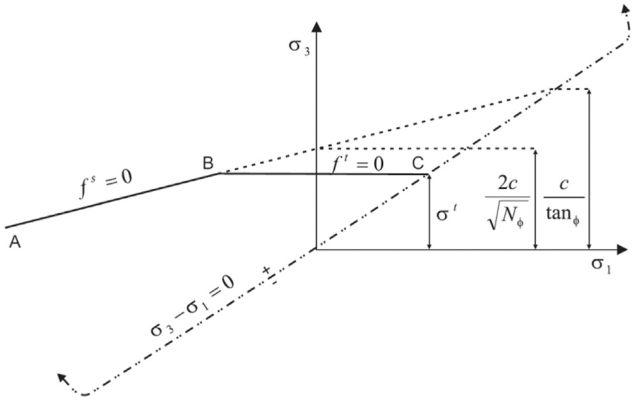

Fig. 2. Mohr-Coulomb failure criterion used for layers.

2.1. Discrete element modelling

The explicit DEM based on finite difference principles originated in the early 1970s was the result of landmark work on the progressive movements of rock masses as 2D rigid block assemblages [24]. This technique was then extended to the modeling of masonry structures [25–27]. Due to the mode of manufacture, a RE wall is a superposition of different earthen layers. The DEM is therefore a pertinent approach to simulate RE walls, because the behaviour of the interfaces between the earthen layers can be taken into account. In the present paper, the 3DEC code (Itasca [28]) was used for the discrete element modelling.

The RE wall was modelled as an assemblage of discrete blocks (earthen layers), and the interfaces between earthen layers (Fig. 3b) were modeled by introducing an interface law. Details about the constitutive models for RE layers and interfaces are presented in [29]. RE layers being assumed to be homogeneous and isotropic, were modeled by blocks that were further divided into a finite number of internal elements for stress, strain, and displacement calculations. The failure surface used in this study was the Mohr-Coulomb criterion with a tension cut-off behaviour [Fig. 2]. The Mohr-Coulomb criterion is expressed in terms of the principal stresses σ_1, σ_2 and σ_3, which are the three components of the generalized stress vector for this model (n = 3). The components of the corresponding generalized strain vector are the principal strains ε_1, ε_2, ε_3· In labelling the three principal stresses so that: $\sigma_1 \leq \sigma_2 \leq \sigma_3$. This criterion may be represented in the plane (σ_1, σ_3), as illustrated in Fig. 2 (recall that compressive stresses are negative). The failure envelope $f(\sigma_1, \sigma_3) = 0$ is defined from point A to B by the Mohr-Coulomb shear failure criterion $f^s = 0$ with $f^s = \sigma_1 - \sigma_3 N_\varphi + 2c\sqrt{N_\varphi}$ and from B to C by a tensile failure criterion of the form $f^t = 0$ with $f^t = \sigma_3 - \sigma_t$ where φ is the friction angle, c is the cohesion, σ_t is the tensile strength, and $N_\varphi = \frac{1 + \sin\varphi}{1 - \sin\varphi}$Note that the tensile strength of the material cannot exceed the value of σ_3 corresponding to the intersection point of the straight lines $f^s = 0$ and $\sigma_1 = \sigma_3$ in the $f(\sigma_1, \sigma_3)$ plane. This maximum value is given by $\sigma^t_{\max} = \frac{c}{\tan\varphi}$The potential function, g^s, used to define shear plastic flow corresponds to a non-associated law and has the form: $g^s = \sigma_1 - \sigma_3 N_\psi$ where ψ is the dilation angle and $N_\Psi = \frac{1 + \sin\psi}{1 - \sin\psi}$

If shear failure takes place, the stress point is placed on the curve $f^s = 0$ using a flow rule derived using the potential function g^s. If tensile failure is declared, the new stress point is simply reset to conform to $f^t = 0$; no flow rule is used in this case.

When the failure takes place in layers, there is no softening or hardening in the post-peak domain, the material corresponds to a perfectly-plastic state. In the post-peak (failure) zone, only the strains continue to increase, the stress remains constant such as a plateau.

Interfaces between earthen layers were modeled by an interface law between the blocks according to the Mohr-Coulomb interface model with a tension cut-off [29]. This interface constitutive model considers