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Pseudo-static scaled-down experiments on dry stone retaining walls: Preliminary implications for the seismic design

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ABSTRACT

Dry stone retaining walls (DSRWs) are vernacular structures which can be found all over the world. Most of them have been built in the 19th century but they can be as old as two hundred years. Because of decades of neglect, many of these walls are highly damaged; however, in the absence of national rules for this peculiar heritage, any intervention on these constructions is made difficult. A number of former studies in France have tried to settle the bases for a standard aimed at designing slope DSRWs. This paper complement those works in order to give clues for a seismic design of slope DSRWs following the simplified approach proposed by the Eurocode 8 and denoted pseudo-static approach.

Firstly, scaled-down experiments have been carried out using a mock-up composed of a wall made of clay bricks retaining a sandy backfill. This mock-up was then tilted and the characteristics of the system at failure were reported and analysed. A particularity of failure in DSRWs is that the failure surface crosses the wall leaving a part of it intact. Secondly, an analytic method based on the limit equilibrium using the Coulomb wedge theory has been designed to predict the tilting angle and validated on the basis of these experimental results. Finally, some preliminary implications for the seismic design of DSRWs have been proposed for walls built in moderate seismicity areas which is typical of mainland France. In low seismicity zones, the extra width required to bear the seismic motion does not exceed 25% of the width identified through the static design. Results are also given for more critical cases associated to zones of higher seismicity as well as for different wall configurations.

1. Introduction

Dry stone retaining walls (DSRWs) are vernacular structures made of rubble stones collected on site and that are hand-assembled without mortar. The weight of the wall, the friction between blocks as well as the peculiar arrangement of the blocks ensure its stability. Despite looking simple, the construction process requires a definite know-how to minimize the porosity within the wall and to achieve a specific arrangement of the blocks able to provide a three-dimensional overall bond strength to the structure.

For centuries, these structures have been used for slope stabilisation against erosion in mountain areas. They have allowed agricultural or wine-growing activities on the artificial terraces and the development of transportation networks in hardly accessible regions. Their intrinsic architectural and landscape quality explain why some of the emblematic sites where this masonry heritage can be found have been inscribed as a part of the World Heritage, UNESCO (e.g. "Valley of Douro", Portugal; "Serra de Tramuntana", Majorca island - Spain; "Lavaux terraces", Switzerland). Recently, some local authorities have envisioned this dry stone heritage as an asset for the economic development of remote territories as a new tourism offer (e.g. "Ruta de pedra en sec", Majorca island, Spain).

Nevertheless, this heritage is very often highly damaged due to decades of neglect. The rehabilitation of these structures remains a significant issue in a context where repairs must be processed without the guidance of national standards that are unavailable in most European countries.

However, some studies have tried to restore the knowledge related to the behaviour of the DSRWs. The first study has been developed in 1834 by Sir John Burgoyne [1]. He studied the impact of the geometry of the walls on their stability confirming the state of the art of this heritage. For the same cross-sectional area, the batter of the external face of the wall gives extra resistance whereas the batter of the internal face gives no added resistance. After this first referenced study, Cooper [2] brought to light the three possible failures for a slope DSRW: sliding, overturning and bulging. The sliding and overturning modes of failure are two plane deformation modes of failure in which the failure surface splits the system into two parts: a lower part of the wall that

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remains intact and that almost does not move during failure and an upper part that falls apart. The bulging mode of failure is either a true three-dimensional mode of failure that is observed for walls built on compressible soils or a plane deformation mode of failure.

Lately, Villemus [3], Colas [4] and Mundell [5] have developed different analytic design methods for plane DSRWs. In particular, Villemus used a method based on the Coulomb wedge to predict the sliding and overturning mode of failure while Colas used a yield design method. These different approaches were validated on a set of full-scale experiments. In a more different way, Mundell used also a limit equilibrium method based on Coulomb's earth pressure where the stability of the wall was checked at each layer of stones in the wall. This programm succeeded in reproducing full-scale experiments where the bulging phenomenon appeared. Recently, numerical studies were performed to model the static behaviour of DSRWs, including the finite element method (FEM) [6], the discrete element method (DEM) [7] or a mixed DEM-FEM approach [8–10]. Finally, more recent studies have allowed to explore the static three-dimensional failure of DSRWs induced by a concentrated load like a vehicle at the surface of the backfill in the case of highway DSRWs [11,12].

However, most of the DSRWs are built in regions where the seismic risk is critical (e.g. in France, Greece, Italy, Portugal, Spain). Even if Eurocode 8 [13] gives a guidance for the design of retaining walls in seismic zones, specificities of DSRWs are not addressed in this standard.

The first works that have taken into account the effect of seismic action on retaining walls were carried out by Mononobe and Okabe [14,15]. The pseudo-static method (known as Mononobe-Okabe method) they designed for this purpose is the one recommended by Eurocode 8 [13]. Further developments have been made by other authors [16,17] to take into account the vertical acceleration and the direct effect of the seismic action on the wall. However, the pseudo-static approach which is a simplified approach for the dynamic problems has some limitations and leads to uncorrect results. Indeed, for high seismic accelerations (above 0.3g), this method greatly over-estimates the seismic action. According to Baziar [18], the estimate of the seismic action in the pseudo-static case can reach a value five times bigger than the estimate using a pseudo-dynamic method. In the pseudo-dynamic approach by Baziar and other authors [18–20], the undulatory characteristic of the seismic motion is taken into account to improve the accuracy of the seismic design method.

As a first step to address the specific design of slope DSRWs, a pseudo-static approach of the seismic problem is herein proposed. First, a set-up including a brick wall and a backfill for experiments is presented. Then, a parametric study addressing the influence of the wall geometry on the seismic resistance of the wall-backfill system was carried out. In a second part, an improved analytical method based on the Coulomb wedge theory is presented and then validated on the basis of the experiences. Finally, some preliminary implications are given for the seismic design of slope DSRWs.

2. Scaled-down model and case studies

2.1. Scaled-down model

2.1.1. General characteristics

For the sake of simplicity, the experimental tests have been carried out on a scaled-down model (Fig. 1) composed of a 10 cm high retaining brick wall loaded by a backfill. The length of the wall has been chosen equal to 40 cm to ensure a plane deformation state behaviour (and to limit side effects on the wall behaviour). This wall and the backfill were placed in a container of 40 cm length, 40 cm width and 25 cm high. A pre-design of the retaining wall has enabled us to point out that the failure surface within the backfill does not intercept the lateral walls of the container (Fig. 2).

The retaining wall was made of small clay bricks of dimensions: 33 mm ∗ 17 mm ∗ 11 mm (length ∗ width ∗ height) = (L ∗ l ∗ h). The

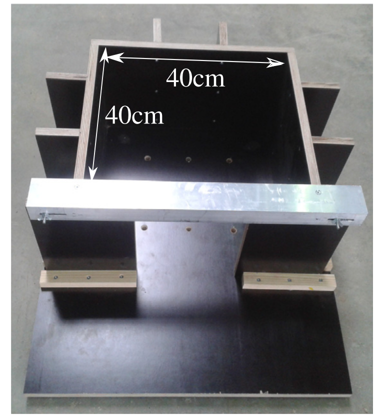

Fig. 1. Container. The length of the wall (placed in the aperture) is variable (maximum length = 40 cm).

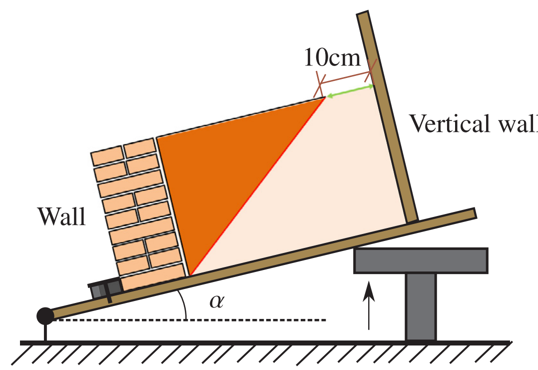

Fig. 2. Cross-section view of the container and the backfill-wall system; gap of 10 cm between the container vertical back wall and the failure surface within the backfill; a piece of wood fixed to the container floor blocks the translational movement of the first row of bricks.

backfill was composed of Hostun sand and the backfill surface was built horizontal. Some sand was poured and glued on the surface floor of the container in order to obtain a friction angle at this boundary similar to the internal friction angle of the sand. For convenience, the lateral walls of the container were made with a plywood panel and no peculiar treatment was added to limit friction between the lateral walls of the container and the backfill.

2.1.2. Properties of the materials

The unit weight of the wall (including pores between blocks) was 14.4 ± 0.27 kN/m^3. The friction angle between blocks has been evaluated to 32 ± 2degr in a previous work [12]. The backfill was composed of Hostun sand: D_{50} = 0.37 mm, D_{10} = 0.2 mm, e_{max} = 1.041 and e_{min} = 0.648 [21]. To create the backfill, the sand was poured from a zero drop height in order to obtain the loosest state for the material. In fact, the experimental relative density was found to be equal to 4%, which corresponds to a unit weight of 13.15 ± 0.45 kN/m^3. The internal friction angle of Hostun sand in a very loose state has been identified by Flavigny et al. [21] to 32° ± 0.5° under a confining pressure of 50 kPa. A further analysis by Quezada et al. [12] confirmed this value for the same conditions as the test considered in this study, where mean confining pressure is much lower (0.7 kPa).

The friction angle at the interface between wall and sand has been evaluated in this study using a tilting test. In this test, a significant part of the wall including glued blocks has progressively been tilted on a 70 mm high layer of sand. The interface friction angle corresponds to the angle between the horizontal and the top sand layer when a slide of the glued blocks is triggered. An average value of 22.7 ± 2° was obtained by means of eighteen repeated tilting tests.

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