ADVANCES ON STRUCTURAL, ENVIRONMENTAL AND ECONOMICAL ANALYSIS OF DRY-STONE RETAINING WALLS

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**Abstract.** *Dry-stone technique is a vernacular but worldwide form of construction, appreciated for its simplicity, robustness, and permeability. Once forgotten or depreciated, this technique is undergoing a recent renewal of interest considering its innovative character in the framework of sustainable development. Yet, this new interest is slowed down by the lack of technical and economical knowledge proving its reliability and relevancy. This paper presents recent developments on design methods and sustainability analysis aiming at enhancing the use of dry-stone masonry in retaining wall construction.*
1 INTRODUCTION

Dry-stone refers to constructions made of rubble or square stones interlocked together without mortar, in order to build a wall or a vault. This technique is a vernacular but worldwide form of construction. Dry-stone accounts for 18% of the retaining structures along the French national road network, representing more than 1000 walls [1], and for 50% of the walls in Great Britain, stretching over 4500 km [2]. Yet, the lack of technical and economical knowledge leads to phasing out the technique for both repair and new constructions.

However, dry-stone is well suited for retaining structures considering its robustness, deformability and permeability. Indeed, it proves relevant in the framework of sustainable development as it relies on local resources and local skills.

The French Ministry of Ecology, Sustainable Development and Energy (MEDDE) is involved in the study of dry-stone retaining structures since 1998. The ENTPE has initiated research aiming at better understanding the mechanical behaviour of dry-stone retaining walls. Collaborations have been engaged with the ENPC on mechanics of dry-stone structures, and then with Ifsttar and CEREMA on Life Cycle Analysis. The present study is part of the French programme for research PEDRA, financed by the MEDDE and involving the four institutions, which aims at developing analytical and numerical methods as well as decision support tools to assess the performance of vernacular masonry structures during their whole life cycle.

This paper presents recent developments aiming at enhancing the use of dry-stone masonry in retaining wall construction. First, a structural analysis model based on yield design is introduced. Two approaches have been developed, and compared to full-scale experiments: a 2D model for upstream walls and a 3D approach for downstream walls subjected to traffic loading. A good practice guide including cross curves of stability based on the 2D approach will be exposed. Then, a sustainability analysis has been undertaken in order to evaluate the ecological and economical impacts of dry-stone constructions, through the case study of a dry-stone retaining wall recently built in France.

2 2D MODELLING OF DRY-STONE RETAINING WALLS

The model first concentrates on plain strain behaviour of dry-stone retaining walls. This hypothesis has been selected in an initial approach for simplicity reasons but also because it is representative for upstream retaining walls or downstream structures when situated far from the road.

2.1 Yield design modelling

Masonry. Dry-stone is difficult to model considering its strong heterogeneity and irregularity: it stands at the frontier between periodic and random material. In this study, it has been decided to idealised the material as a periodic medium (Fig. 1a). This hypothesis enables the periodic homogenisation of dry-stone in the framework of yield design theory as performed by de Buhan and de Felice [3]. The stones are considered as infinitely resistant, with their joints complying with a purely frictional Mohr-Coulomb criterion. The homogenisation process provides the anisotropic yield criterion, only depending on the block friction angle $\varphi$ and dimensions $a$ and $b$. Masonry is now considered as a homogeneous material (Fig. 1b).
Structure. The structure under consideration comprises the wall and its backfill, considered as a Mohr-Coulomb material. The geometrical characteristics of the structure are defined in Fig. 2a. The sole action taken into account in the model is the unit weight of the structure, $\gamma_m$ for the masonry, and $\gamma_s$ for backfill.

Considering these data, the bearing capacity of the structure is assessed using yield design upper bound approach; more information can be found in [4]. Two virtual failure mechanisms are explored:

- a translation of the wall $v$ and the backfill $v_s$ (Fig. 2b);
- a rotation of the wall $v$ and a shearing of the backfill $v_s$ (Fig. 2c).

The upper bound approach relies on the virtual work principle. The work of the external forces $W^e$ and the maximum resisting work $W^{rm}$ are calculated for each mechanism presented above. This enables the expression of a necessary condition of stability, for all the kinematically admissible mechanisms:

$$W^e \leq W^{rm} \implies B \geq f(h, \lambda_1, \lambda_2, \alpha, \beta, a, b, \gamma, \gamma_s, \varphi, \varphi_s, v, v_s, \Psi, \Psi_s)$$ (1)
An analytic expression of the minimal thickness ensuring the stability of the structure \( B^{\text{min}} \), only depending on the characteristics of geometry, loading and resistance, is finally given by the minimisation of the previous expression \( f \) towards the kinematic parameters \( v, v_s, \Psi \) and \( \Psi_s \):

\[
B^{\text{min}} = \min_{v, v_s, \Psi, \Psi_s} f(h, \lambda_1, \lambda_2, \alpha, \beta, a, b, \gamma, \gamma_s, \varphi, \varphi_s)
\tag{2}
\]

2.2 Full-scale experiments

Experimental data on plain strain behaviour of dry-stone retaining walls are quite sparse [5, 6]. Yet, the strong heterogeneity of the structure as well as the specific interaction with the backfill make it necessary to undertake full-scale experiments. The model previously exposed has been validated by an in situ experimental campaign on four full-scale dry-stone walls.

Experiments consist in building self-standing walls, which are backfilled until failure by a pulverulent soil. Walls are built by dry-stone master craftsmen with different stones and cross-sections to evaluate the influence of these parameters: the physical and geometrical characteristics of the walls are collected in Tab. 1. Walls have been designed to fail at the end of the backfill, using the model presented in section 2.1.

Table 1: Geometrical and physical characteristics of the experimental walls loaded in plain strain by a pulverulent backfill.

<table>
<thead>
<tr>
<th>Wall</th>
<th>Wall C1g</th>
<th>Wall C2s</th>
<th>Wall C3s</th>
<th>Wall C4l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall height ( h ) (m)</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>Wall thickness at the base ( B ) (m)</td>
<td>0.60</td>
<td>0.60</td>
<td>0.70</td>
<td>0.65</td>
</tr>
<tr>
<td>Wall batter ( \lambda_1 ) (°)</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Wall counter-slope ( \lambda_2 ) (°)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Joint inclination ( \alpha ) (°)</td>
<td>3.4</td>
<td>3.4</td>
<td>9.1</td>
<td>9.1</td>
</tr>
<tr>
<td>Backfill slope ( \beta ) (°)</td>
<td>26.4</td>
<td>31.7</td>
<td>32.6</td>
<td>34.9</td>
</tr>
<tr>
<td>Wall unit weight ( \gamma ) (kN/m³)</td>
<td>21.0</td>
<td>20.0</td>
<td>20.0</td>
<td>21.8</td>
</tr>
<tr>
<td>Soil unit weight ( \gamma_s ) (kN/m³)</td>
<td>14.9</td>
<td>14.9</td>
<td>14.9</td>
<td>14.9</td>
</tr>
<tr>
<td>Block friction angle ( \varphi ) (°)</td>
<td>27</td>
<td>25</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Soil friction angle ( \varphi_s ) (°)</td>
<td>37.7</td>
<td>37.7</td>
<td>37.7</td>
<td>37.7</td>
</tr>
<tr>
<td>Ultimate backfill height ( h^+_s ) (m)</td>
<td>–</td>
<td>2.41</td>
<td>2.96</td>
<td>2.95</td>
</tr>
</tbody>
</table>

Main results of the experiments are shown in Tab. 1; results are detailed in [7]. The first experiment has failed due to a technical problem. The three following experiments show good agreement between theory and practice, both for quantitative and qualitative results. Actually, experiments show the wall overturning around its toe along its full length (Fig. 3), thus validating the hypothesis of plain strain and rigid body behaviour. Yield design proves relevant to evaluate the stability of dry-stone retaining structures.

2.3 Cross curves and design recommendations

A simplified version of the model has been implemented in cross curves of stability. Cross curves provide the minimal thickness of the wall at the base \( B \), depending on:
Figure 3: Test on a 2.50 m high wall made of schist backfilled until failure by round gravel: view of the backfill loading (a), overturning of the wall (b) and plot of three cross-sections of the wall (c).

- the type of stone: schist or soft limestone;
- the wall height: from 1.5 m to 6 m;
- the wall batter: 0, 10 or 20%;
- the friction angle of the backfill: from 0 to 50°;
- the slope of the backfill: 0, 10 or 20°.

The following hypotheses have been made:
- the upstream face of the wall is vertical, meaning the counter-slope is null;
- the backfill soil is purely frictional, meaning the cohesion is null;
- safety factors of 1.2 on sliding and 1.5 on toppling have been applied.

Given these parameters, cross curves enable the determination of the minimal thickness of the wall at its base (Fig. 4).

These cross curves are gathered in a good practice guide, which provides recommendations on the design and construction of dry-stone retaining walls [8]. Ongoing developments deals with taking into account cohesion in the soil and overload on the backfill.

3 TOWARDS A 3D MODELLING OF DRY-STONE RETAINING WALLS

The previous plain strain study has been extended to 3D case in order to deal with downstream retaining walls subjected to traffic loading. Actually, axle loads induce an out-of-plane effect that cannot be taken into account in plain strain hypothesis and requires a 3D modelling of the wall and the backfill.
3.1 Yield design modelling

The 2D yield design approach is extended to a 3D modelling. The dry masonry is idealised as a periodic medium (Fig. 5a) and homogenised in the framework of yield design theory (Fig. 5b). The unit cell is a parallelepiped composed of 13 blocks of masonry. The stones are still considered as infinitely resistant, with their joints complying with a purely frictional Mohr-Coulomb criterion. The homogenisation process provides the anisotropic yield criterion, only depending on the block friction angle \( \phi \) and dimensions \( a, b \) and \( c \). More details can be found in [9].

The structure is assessed resorting to yield design. Geometrical characteristics are given in Fig. 6a. The actions taken into account in the model are again the unit weight of the structure, \( \gamma_m \) for the masonry, and \( \gamma_s \) for backfill, but also a concentrated load \( F \) over the backfill at a distance \( d \) from the wall, figuring the action of an axle load. The virtual failure mechanism explored in this study comprises translations of the wall and the backfill (Fig. 6a).
The application of the yield design upper bound approach enables the expression of a necessary condition of stability, for all the kinematically admissible mechanisms:

\[ W^e \leq W^{rm} \Rightarrow B \geq f(h, \lambda_1, \lambda_2, \alpha, a, b, c, d, \gamma, \gamma_s, F, \varphi, \varphi_s, \eta, d^*, \chi, \xi, \mu, \theta) \] (3)

An expression of the minimal thickness ensuring the stability of the structure \( B^{\text{min}} \), only depending on the characteristics of geometry, loading and resistance, is finally given by the minimisation of the previous expression \( f \) towards the kinematic parameters \( \eta, d^*, \chi, \xi, \mu, \theta \):

\[ B^{\text{min}} = \min_{\eta, d^*, \chi, \xi, \mu, \theta} \ f(h, \lambda_1, \lambda_2, \alpha, a, b, c, d, \gamma, \gamma_s, F, \varphi, \varphi_s) \] (4)

### 3.2 Full-scale experiments

The validity of the model is tested through full-scale experiments. In this campaign, the wall and its backfill were built self-standing, the structure being loaded by a concentrated solicitation figuring the action of an axle (Fig. 6b). This concentrated load was applied using an excavator acting on a 0.60 × 0.60 m metallic foundation. The physical and geometrical characteristics of the walls are collected in Tab. 2.

Main results are shown in Tab. 2 and detailed in [9]. This campaign proves that a concentrated load has little influence if situated beyond 2 m from the wall, meaning that in this configuration, the 2D model previously exposed is adequate. It also shows a substantial difference between experiments and theory; two main factors can account for this difference. First, the experimental wall was built thin in order to reach failure: this induces that the number of blocks in the thickness of...
Table 2: Geometrical and physical characteristics of the experimental retaining walls loaded by a concentrated load.

<table>
<thead>
<tr>
<th></th>
<th>Wall L1</th>
<th>Wall L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall length $L$ (m)</td>
<td>10.5</td>
<td>10.5</td>
</tr>
<tr>
<td>Wall height $h$ (m)</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Wall thickness at the base $B$ (m)</td>
<td>0.69</td>
<td>0.66</td>
</tr>
<tr>
<td>Wall batter $\lambda_1$ (°)</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Wall counter-slope $\lambda_2$ (°)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wall unit weight $\gamma$ (kN/m$^3$)</td>
<td>20.3</td>
<td>20.3</td>
</tr>
<tr>
<td>Backfill unit weight $\gamma_s$ (kN/m$^3$)</td>
<td>14.9</td>
<td>15.4</td>
</tr>
<tr>
<td>Block friction angle $\varphi$ (°)</td>
<td>36.0</td>
<td>36.0</td>
</tr>
<tr>
<td>Backfill friction angle $\varphi_s$ (°)</td>
<td>37.7</td>
<td>37.7</td>
</tr>
<tr>
<td>Overload-wall distance $d$ (m)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Ultimate overload value $F^+$ (kN)</td>
<td>56</td>
<td>63</td>
</tr>
</tbody>
</table>

the wall may be insufficient to comply with homogenisation theory. Then, the sensors recording the displacement of the wall depending on the load show a difference between the friction angle measured in situ in the wall and the friction angle measured by laboratory tests. A parametric analysis show the strong influence of the friction angle of the stones in this model. Ongoing research explores the possibility of considering a different friction angle for vertical and horizontal joints.

4 SUSTAINABILITY ANALYSIS OF DRY-STONE RETAINING WALLS

Dry-stone constructions can be found all around the world, where the supply of stone is sufficient. This technique has been massively used for its simplicity as it requires few heavy equipment and transport. These characteristics nowadays prove relevant in the framework of sustainable development. This study aims at demonstrating the performance of dry-stone masonry over other common techniques of construction.

4.1 Description of the case study

The sustainability analysis is carried out through the case study of a recent construction in the district of Felletin (Creuse, France). Professional dry-stone masonry craftsmen have been appointed to build a dry-stone retaining wall downstream a local road in 2012. This wall is 3 m high and 50 m long, and made of recovered granite blocks (Fig. 7). Works were completed in six weeks and required 12 masons.

4.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a standard method referring to NF EN ISO 14040 [10] and NF EN ISO 14044 [11]. It consists in evaluating the resource usage and environmental impacts of a product or a service. The four steps identified in the standards are detailed below.

**Goal and scope definition.** LCA starts with the definition of the context and research topic of the study. Here, the functional unit is a civil engineering construction retaining a backfill supporting a vehicle road during 100 years. In a first approach, the boundaries of the system are limited to the construction of the retaining structure: production of materials, transport of materials and
equipment, and construction stage. The study concentrates on the dry-stone wall, the comparison with a concrete solution being discussed as a perspective.

**Life cycle inventory.** The data related to the construction have been collected with the support of the dry-stone craftsmen who built the wall; main data are presented in Tab. 3. This enables the inventory of flows involved in the construction.

<table>
<thead>
<tr>
<th>Material production</th>
<th>Granite</th>
<th>110 m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>Materials</td>
<td>414 t.km</td>
</tr>
<tr>
<td></td>
<td>Heavy equipment</td>
<td>3330 t.km</td>
</tr>
<tr>
<td>Construction stage</td>
<td>Diesel for equipment</td>
<td>960 L</td>
</tr>
<tr>
<td></td>
<td>Personnel transport</td>
<td>15750 km</td>
</tr>
</tbody>
</table>

**Life cycle impact assessment.** The flows of the life cycle inventory are used as an input to calculate the environmental impacts of the construction of the dry-stone wall. Ten impact assessment categories have been chosen for this study, referring to the methodology developed at the Center of Environmental Science of Leiden University in 2001 (CML 2001) [12]. The evaluation has been performed using Simapro 7.3.3 software and the Ecoinvent database. It enables the identification of the most important processes on environmental impacts. Two hypotheses have been explored on the origin of the stones composing the wall: recovered stones, in accordance with the real project, and stones from a local carrier, to include general cases.

**Interpretation.** Considering the stones recovered, the contribution of the material production stage is very low (Fig. 8) as the sole inputs are the infill material and the amortisation of heavy equipments. In the case of dry-stone reconstruction, this assumption is often fully or partially fulfilled as the stones can be easily re-used. When including the production of stones from a local carrier, the contribution of the material production increases but proves equivalent to transport and constructions stages. This repartition is specific to this project, as material production usually stands for the main part of environmental impacts in civil engineering works.
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Figure 8: Identification of the contribution of material production, transport and construction stages in the environmental impacts of the construction of the dry-stone retaining wall in Felletin: recovered stones (a) and stones from a local carrier (b).

4.3 Economic issues

One of the main reasons explaining the drop of dry-stone technique in modern construction is based on its cost. The dry-stone wall in Felletin cost 2500 €/ml. Economic data on civil engineering works are very difficult to find and compare considering the specificity of each project. However, this can be compared to figures given in [2], where the cost of the replacement of all dry-stones retaining walls in Great Britain was estimated at 1400 €/ml in 1999. This can also be compared to expert advice [13] estimating the cost of a 3 m high concrete wall to 3200 €/ml. Thus, the cost of dry-stone walls stands in the same value range.
4.4 Ongoing research

Ongoing research on this work deals with comparisons with different technical solutions. Actually, LCA is often used to compare different solutions, with the objective minimizing environmental impacts. Solutions chosen here are jointed masonry, gabions and concrete walls.

Perspectives also includes the integration of maintenance hypotheses over a hundred years in order to analyse the structure on its whole life cycle. Actually, recent studies [14] have proved the importance of considering the life cycle of the structure to chose the most appropriate solution. The LCA will be repeated on the different technical solutions with the maintenance stage. It will be completed with a Life Cost Cycle to analyse the economical advantages of each technique.

5 CONCLUSION

Dry-stone has been widely used to build retaining walls in the XIXth and early XXth centuries in Europe. However, dry-stone has been abandoned in favour of modern techniques and is hardly ever or no longer used in new construction and even reconstruction, because considered as unreliable and expensive. Yet, this technique has proved its robustness and durability thanks to its deformable and permeable character. Indeed, dry-stone offers obvious aesthetics and patrimonial qualities.

This study presents the works undertaken during the past ten years in the French Ministry of Ecology, Sustainable Development and Energy to characterize the performance of dry-stone constructions. Models based on yield design theory have been developed to provide rational and reliable design prescriptions. A plain strain model for upstream wall has been validated on full-scale experiments and implemented in a good practice guide. It has been extended to a 3D model which validation is still ongoing. Besides, the sustainability of dry-stone construction has been evaluated through a Life Cycle Assessment, showing the very low contribution of material production stage in the environmental impacts. Perspectives on this work include comparisons with other techniques of construction and integration of a maintenance scenario to deal with the whole life cycle of the structure.

These studies contribute to enable the dissemination of information on the relevancy and the performance of dry-stone structures, thus encouraging reconstruction and new construction.

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