# STRENGTHENING MASONRY DAMS BY MEANS OF DOWNSTREAM BACKFILLS

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## ABSTRACT

*Many old masonry dams suffer from a lack of safety margin due to their ageing or the new criteria related to the latest regulations and standards. An easy way to strengthen a masonry dam is to put in place a backfill against its downstream face, which brings a beneficial force opposite to the water thrust. This article presents the 30 years' experience of the strengthening of masonry dams in France by means of downstream backfills.*

*For the backfill material, it is recommended using a non-cohesive rocky material – 0/400 mm - with a friction angle comprised of approximately and 40°. It allows on the one hand to reduce the downstream slope of the backfill in comparison with soil material and on the other hand to obtain a higher beneficial force in comparison with blocky rock material. The main difficulty is to assess this beneficial force brought by the rocky backfill. A simple method to calculate this force is presented in this article. This method which can be applied for any geometry gives results close to FEM calculations, and is always on the safe side.*

## 1. INTRODUCTION

### 1.1 Masonry dams in France

72 masonry dams - more than 15 m high - have been built in France for 350 years. The oldest one – still in use - is Saint-Férréol dam built in 1672. Masonry dams represented the majority of the dams built in France during the 19th century and the beginning of the 20th century.

From the 1850s, the profiles of the masonry dams became thinner – with a slope equal to 1vertical for 0,6 or 0,7 horizontal- to optimize the masonry volume until the failures of Bouzey dam in 1895. These accidents highlighted the role of the water pressure in the masonry and in the foundation.

From the beginning of the 20th century, the profiles of the dams were thicker and the dams progressively drained.

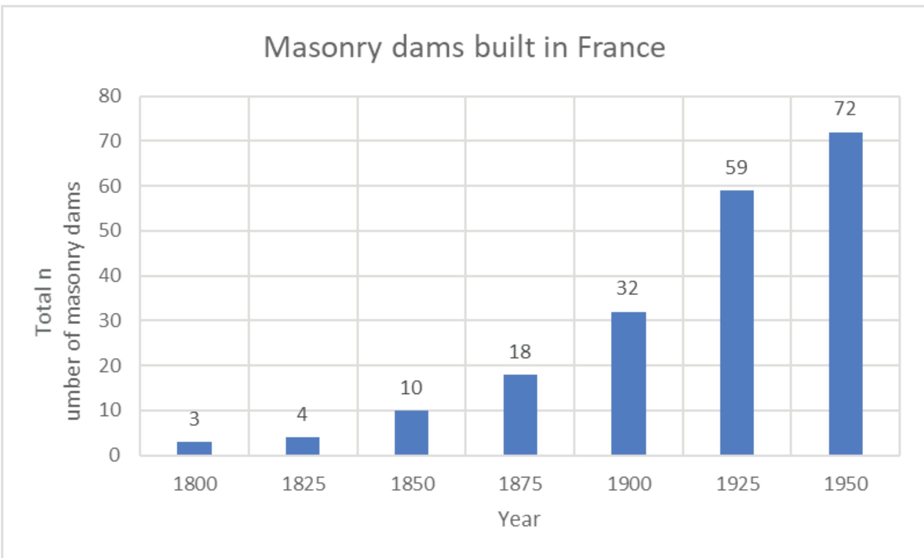


**Figure 1** : Total number of masonry dams in France versus time

From our experience, the old masonry dams suffer from the following main pathologies:

- Watertightness defect of the masonry (80% of French masonry dams)
- High permeability or water pressure in foundation (45 % of French masonry dams)
- Global instability (insufficient safety margin) (25 % of French masonry dams)

The following remedial works were carried out so far:

- Improvement of the watertightness of the masonry (80% of French masonry dams)
- Grouting and drainage of the foundation (45 % of French masonry dams)
- Strengthening by anchors (10 % of French masonry dams)
- Strengthening by downstream backfill (13 % of French masonry dams)

Following French masonry dams strengthened by a downstream backfill may be mentioned:

**Table 1**. French masonry dam strengthened by downstream backfill in the last 35 years

| | **Dam height** | **Dam slope** | **Backfill slope** |
|---|---|---|---|
| Joux | 30 m | 0.84h/1v | 1,4h/1v |
| Ternay | 41 m | 0.7h/1v | 1,4h/1v |
| Vérut | 21 m | 0.75h/1v | 1,5h/1v |
| La Gimond | 19 m | 0.8h/1v | 1,8h/1v |
| Pas-de-Riot | 36 m | 0.73h/1v | 1,7h/1v |
| Dardennes | 37.5 m | 0.84h/1v | 1,5h/1v |

See references [1], [2] & [3]

## 2. THE PRINCIPLES OF A STRENGHTENING BY MEANS OF DOWNSTREAM BACKFILL

### 2.1 Main constraints

Two opposite constraints govern the design of a strengthening by means of a downstream backfill.

On the one hand it is often advantageous – for lack of space or from economical point of view – to design a backfill with a steep slope. On the other hand, the beneficial thrust is reduced when the material used for the backfill presents a high friction angle. The higher is the friction angle, the lower is the beneficial thrust.

It is thus recommended opting for an economical compromise using rocky material with a maximum diameter of 400 mm.

### 2.2 Rockfill characteristics

Usually, a rocky material with a friction angle of approximately 40° is selected. As this friction angle is difficult to measure, it is recommended using rocky material with a continuous grading curve, with a maximum diameter of 400 mm. The percentage of fines – below 80 µm - can reach 8 to 10 %. This kind of material is easy to find and often cheap.

To ensure the stability of the backfill, the material shall be permeable – $k > 10^{-3}$ m/s. The maximum percentage of fines is dictated by the global permeability of the material. Permeability tests – as Matsuo tests – shall be performed to check that fines % above 5% can be authorized.

The backfill does need to be too compacted so as not to increase too much the friction angle. Usually two passes of roller are enough for compaction. The material in vicinity of the downstream face of the backfill shall be compacted with more energy to ensure the stability of the slope – skin effect.

### 2.3 Typical cross-section

The typical cross-section is presented in Figure 3.

A transition layer – sand - is put between the backfill and the downstream dam face to improve the transmission of the beneficial thrust to the dam.

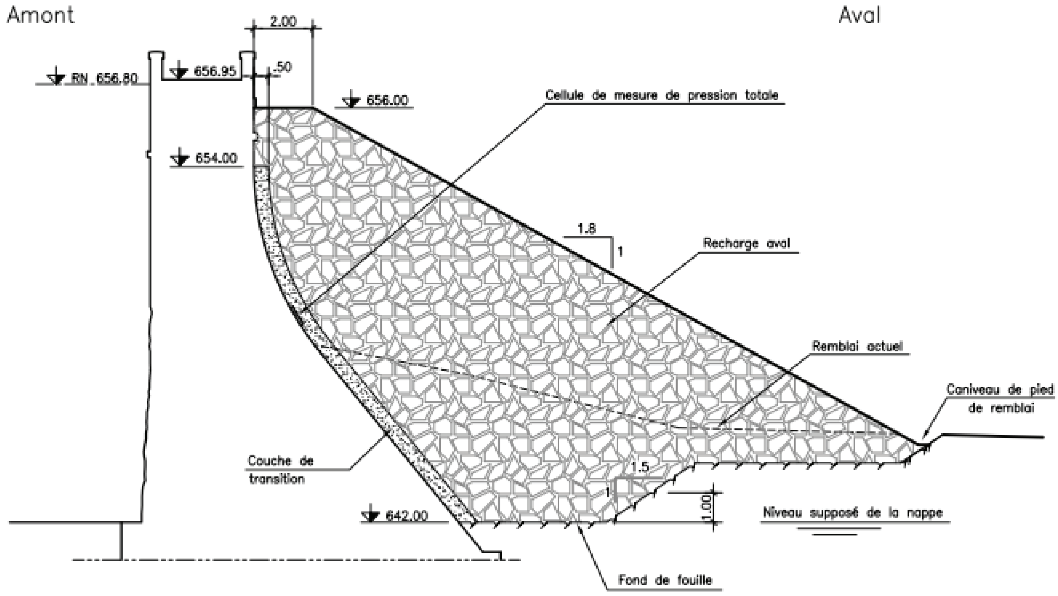


**Figure 2** : Typical cross-section

## 3. ASSESSMENT OF THE BENEFICIAL THRUST

It is difficult to assess the beneficial thrust brought by a backfill as the common formula used for retaining walls cannot be applied. Indeed, active or passive earth pressure formulae cannot be applied as the displacement of the dam is too small. Moreover, the formula used for estimating backfill pressure at rest – as Jaky's formula for coefficient of lateral pressure at rest : $K_o = (1 - \sin \varphi)$ – cannot be used as it is valid for a semi-infinite horizontal backfill. The geometries of the dam and its backfill are too complex.

A new method inspired by the Coulomb's wedge method is proposed by the authors.

### 3.1 Coulomb's wedge method

At a certain level, let's consider the equilibrium of a rockfill wedge defined by a downstream inclined plane. The weight ($\vec{P}$) of this wedge can be broken down into two reactive forces:

- A force $\overrightarrow{(A)}$ acting on the downstream face of the dam – the beneficial thrust
- A force ($\vec{R}$) applied on the remaining part of the backfill by the wedge.

Préciser les points d'application de ces forces

Against a moving wall, the backfill thrust is given by a Coulomb's wedge defined by an inclined plane at 45°+ φ/2 – φ being the effective friction angle of the backfill material.

To obtain a unique breakdown of the forces, it is necessary to make the following assumptions on the directions of the forces:

- The direction of the force $\overrightarrow{(A)}$ is inclined of ϕ/2 to the perpendicular to the dam downstream face
- The direction of the force ($\vec{R}$) is inclined of φ to the perpendicular to the wedge downstream plane.

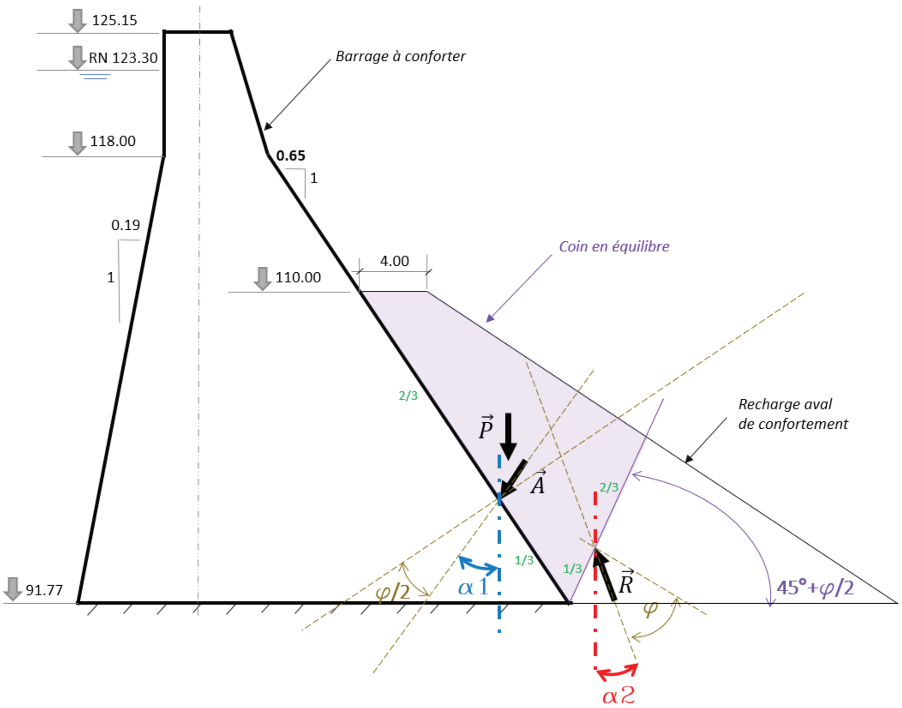


**Figure 3** : Breakdown of the forces applied on the Coulomb's wedge

The following beneficial thrust is obtained:

A = P /(cos (α1) (1 + tg(α1)/tg(α2))

with

$\alpha_1$ = β - φ/2  ( β angle of the downstream dam face with horizontal)

$\alpha_2$ = 45 - φ/2

If we assume less friction between the remaining part of the backfill and the Coulomb's wedge - the force ($\vec{R}$) becomes closer to the perpendicular to the downstream wedge plane - $\alpha 2$ is increasing – the horizontal thrust A increases.

If we assume less friction between the Coulomb's wedge and the downstream dam face – $\alpha 1$ is increasing – the horizontal thrust A increases.

As intuitively felt, the more the friction, the less the beneficial thrust. The force A assessed as above appears to be the minimum theoretical thrust.

## 3.2 Comparison with FE method and Jaky's formula

In order to validate this new method, comparisons with FEM calculations have been carried out for some dams. The differences are small.

The detailed calculation performed for Dardennes masonry dam is provided as an example.

Dardennes dam is a 37.5 m high masonry dam which was built in 1912. The behavior of the strengthened dam was assessed with a non-linear Finite Elements Model.

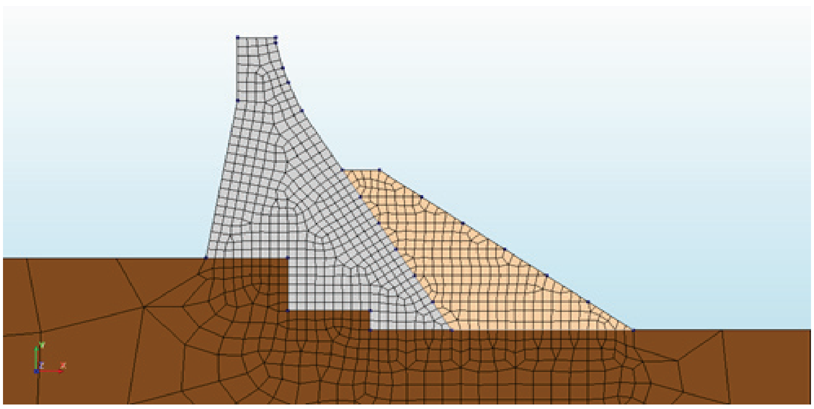

**Figure 4** : FE model (Dam in grey – Backfill in orange)

The beneficial thrust was estimated by both methods with the following assumptions:

- Backfill friction angle: 40 °
- Friction angle between the dam and the foundation: 45 °

The main results are summarised in the table below.

**Table 2** : Dardennes masonry dam - Beneficial thrust calculated by both methods

| | **Horizontal thrust** | **Vertical thrust** | **Total thrust** |
|---|---|---|---|
| EF method | 0.72 MN/m | 0.91 MN/m | 1,16 MN/m |
| Coulomb's wedge method | 0.71 MN/m | 0.94 MN/m | 1,18 MN/m |
| Difference | 2% | 4 % | 2% |

For the same dam, the Jaky's formula for lateral earth pressure at rest has been also used. A coefficient of lateral earth pressure $K_0$ of 0,36 is obtained, to be compared with the coefficient calculated with Coulomb's wedge method of 0,24 . The thrust force for Coulomb's wedge method has been assessed to be equal to $½.K_0.\gamma.h^2$ with γ the backfill unit weight and h the backfill height. The Jaky's formula - $K_o = (1 - \sin \varphi)$ - is far too optimistic by 50%.

### 3.3 Comparison with site measurements

Six Total pressure cells measuring the total pressure applied by the backfill on the dam were installed on Pas-de-Riot dam which was reinforced with a downstream backfill in 2018.

The first measurements show backfill pressures approximately 30 % above the value calculated with the Coulomb's wedge method.

These first results shall be taken with care as they are very sensitive to various parameters difficult to control, such as the exact inclination of the cells.

## 4. CONCLUSION

The objective of this article was to present the French experience on the strengthening of masonry dam by means of downstream backfills. Six French old dams were successfully reinforced with this technique in the last 35 years. Intuitively, the downstream backfill brings a beneficial force opposite to the upstream water thrust. As the geometry of the downstream dam face and of the backfill is complex, the classical formula for retaining walls cannot not be used.

A simple method using Coulomb's wedge theory has been developed to assess the beneficial thrust brought by the rocky backfill. This method gives values theoretically on the safe side. Comparisons with more complex FE models showed that this method is robust.

## REFERENCES

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