A methodology for the design of dam spillways with wedge shaped blocks based on numerical modeling

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Abstract

Wedge shaped blocks spillways are an innovative solution that allows spilling over the downstream shoulder of earth and rock-fill dams in a safe way. However, they have been barely used as main spillway due to the lack of practical design criteria. An innovative procedure for computer-aided design of wedge shaped blocks spillways is presented in this paper. It includes the design of the drainage and supporting layer considering its seepage capacity and stability. The leakage flow through the joints between blocks is estimated by means of a numerical model calibrated and validated from experimental results. Stability against sliding of the downstream shoulder or the drainage layer is ensured, considering the properties of the granular material selected by the designer and non-linear resistance laws. The procedure will also suggest the shape of a toe protection.

1 Introduction

Wedge shaped blocks (WSB) are an innovative solution to protect the downstream shoulder of earth and rock-fill dams and levees against superficial erosion in overtopping scenarios in a cost effective way. The stability of WSB is based on the positive and negative pressure distribution over the block sides, which ensures its stability together with the overlapping of contiguous blocks (Figure 1).

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- Dam spillway
- ACB
- wedge-shaped-block protections
- CFD
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This paper shows a procedure for computer-aided design of WSB spillways, which ensures the stability against sliding of the downstream dam shoulder with a sloping toe protection. It also allows defining the appropriate thickness of the drainage layer (according to the type of dam), to avoid its saturation.

2 Drainage flow

2.1 Introduction

One of the most important aspects to design WSB spillways is the estimation of the expected leakage flow through the joints between adjacent blocks and the orifices. It depends on three parameters: the slope of the spillway, the overtopping flow and the size of the WSB, which in turn determines the length of joints per surface unit.

If this drainage flow is not properly conveyed to the downstream toe, the downstream shoulder can be saturated and generate uplift on the lower side of the WSBs leading to instability. This affects the stability of the downstream shoulder and therefore the whole dam safety.

We used physical tests to calibrate and validate a numerical model that allowed obtaining results beyond the limited discharge rates and geometry of the laboratory facilities.

2.2 Numerical model

The numerical method is based on a mathematical approach in which the blocks and joints are considered as a continuum with a head loss law. This method is widely used for the numerical modeling of seepage into porous materials, and is based on the assumption that water can flow through the whole granular media, without taking into account the shape and distribution of the ducts or the solid impermeable areas of the stones. Then a head loss law \(i\) is fixed to properly simulate the head loss that takes place when the water flows through the real ducts of the porous medium, considering the following expression:

\[ i = a \cdot v \]

Where: \(i\) is the hydraulic gradient; \(a\): coefficient of permeability and \(v\): seepage velocity.

In the same way, a WSB spillway can be considered as ducts (joints and orifices), embedded in a solid and impermeable matrix (body of the block), so the infiltration process can be reproduced with an appropriate head loss law, where coefficient \(a\) is constant for any slope and drainage flow, because it only depends on the size and shape of blocks that define the permeability of the system composed of joints, orifices and block bodies. Figure 3 shows a schematic drawing of this numerical approach.

The finite element code used to solve this numerical approach was one of the applications implemented in the open-source environment Kratos Multi-Physics [8-9], which solves according to an Eulerian framework with a fixed mesh the full Navier-Stokes equations, modified by addition of the head loss law \(i\) as dissipation term, to take into account porous fluid regions and clear fluid regions in the calculus domain. For the improvement of the simulation efficiency an edge based approach and a level set technique to track the evolution of the free surface is implemented. Turbulence is simulated without a specific model for this purpose, due to the Orthogonal Sub-scales Stabilization implemented [10-11]. The complete description of the numerical approach used was described by Larese et al. [12]. This application has already been successfully applied to several problems in dam hydraulics [13-15].

2.3 Calibration and validation of the head loss law

A calibration and validation process was performed to achieve an appropriate and reliable expression for the head loss law. For both, physical and numerical tests were carried out (Figure 4).

The physical tests were performed at the CEDEX laboratory by staff of the Technical University of Madrid. The test facility consisted on a WSB spillway with height 4.7 m, width 0.5 m and downstream slope 2:1. The discharge flows tested were 200 and 240 l/s/m, and the infiltration length gauged was 6.5 m (32 rows). The measurement uncertainty of the devices for recording drainage flow is lower than 3 l/s/m. The tested blocks were the patented model ACUÑA (Figure 5), scaled to set 3 blocks per row.
2.4 Results

Once the calibration and validation processes were completed, a set of 3D numerical simulations were carried out in order to obtain infiltration results for several configurations of the spillway, beyond the limited capabilities of the laboratory facilities. In this way four spillway slopes (1.5, 2.0, 2.5 and 3.0), five discharge flows (200, 300, 400, 600, 1000 l/s/m) and four lengths of spillway (8, 16, 32, 48 rows) were simulated. Figure 7 shows these results.

These numerical tests allow determining the infiltrated flow for the common range of slopes of rockfill and earth dams (1.5-3) and a maximum limit of 48 rows, for homothetic blocks to that tested applying Froude scaling.

3 Calculation procedure

3.1 Solutions proposed to each type of dam

The way to drain the infiltration flow is a key aspect to design WSB spillways and depends on the type of dam.

The dam body of homogeneous dams consists of an impervious material. Therefore, a drainage layer must be placed so to avoid uplift pressure on the bottom side of the blocks, with an adequate hydraulic capacity to drive the infiltration flow to the toe without becoming pressurized (Figure 8).

For validation, two numerical tests were carried out with discharge flow of 160 and 200 l/s/m and the value of coefficient $a$ previously obtained. The resulting infiltration flow rates were compared to those obtained in corresponding physical tests. The discrepancies between physical and numerical infiltration flow were 1.77 l/s/m and 0.87 l/s/m, which represent 13.3 % and 5.0 % of the infiltration flow, both within the measurement uncertainty range of the recording devices.
The shoulder of rockfill dams is highly permeable and leakage can flow through towards the impervious boundary defined by the foundation (Figure 9). In order to keep away blocks from uplift pressure the rockfill permeability must be sufficient to avoid contact between the bottom side of the blocks and the water free surface of the seepage net.

The design procedure ensures that there is no water pressure under the blocks, which could affect its stability. In order to achieve this goal two solutions were proposed according to the type of dam (Figure 10).

For both, the design includes a flip bucket to drive separately the overtopped flow and the infiltration flow. The flip bucket structure was successfully used in Barriga Dam [17], and consists of a concrete perimeter frame filled with porous material, depending on the type of dam. Moreover the flip bucket structure helps to support the blocks. Also for both solutions, a toe protection is disposed to drain the infiltration flow (Figure 11).

3.2 Calculation algorithm

The design procedure proposed has as cornerstone the numerical drainage tests showed previously. Based on it an algorithm for designing the whole spillway for a previously chosen block size was developed, and its flowchart is shown in Figure 12. The algorithm reaches the solution through a process of successive attempts and can be programmed for automation.
The main steps of the algorithm are summarized below.

**STEP 0 - Initialization**
- Calculation of the stable saturated slope for the toe protection [18], according to:
  \[
  F_r = \frac{1}{Y_{e, sat}} \left( Y_{e, sat} - \frac{Y_w}{\cos \alpha} \right) \cdot \frac{\tan(p)}{\tan(\alpha)}
  \]
  Where: \( F_r \) is safety factor against mass sliding of toe protection; \( Y_{e, sat} \) saturated specific weight of the material; \( Y_w \) specific weight of water and \( \phi \): friction angle.
- Calculation of an initial height of training walls from broad crested weir discharge equation:
  \[
  q = \frac{Q}{B} = \frac{2}{3} \cdot 0.577 \cdot \sqrt{2 \cdot g \cdot h^3}
  \]
  \[
  h_{c0} = K \cdot h
  \]
  Where: \( q \) unit discharge flow; \( Q \): total discharge flow; \( B \): width of spillway; \( h \): height of training walls without safety factor; \( h_{c0} \): height of training walls considering safety factor; \( K \): safety factor and \( g \): gravity acceleration.
- Calculation of initial height of toe according to the expression:
  \[
  H_{t0} = \frac{h_{c0}}{\cos \beta}
  \]

Where: \( H_{t0} \): initial height of toe; \( h_{c0} \): initial height of training walls and \( \beta \): dam slope angle. A scheme of the geometrical meaning of the previous equation is shown in Figure 13.

**STEP 1 – Geometric update**
- Updating of toe height
  \[
  H_t = H_{t0} + \Delta H_t
  \]
  Where: \( H_t \): updated height of toe; \( H_{t0} \): height of toe for the previous iteration and \( \Delta H_t \): increase of height fixed by designer (Figure 14). For the first run of step 1: \( H_{t0} = \Delta H_t \); \( \Delta H_t = 0 \)

- Updating of training walls height:
  \[
  h_c = H_t \cdot \cos \beta
  \]
  Where: \( H_t \): toe height; \( h_c \): training walls height and \( \beta \): dam slope angle. The geometrical relation between parameters is shown in Figure 14.

**STEP 2 – Infiltration flow estimation**
- Calculation of homothetic factor
  \[
  \lambda = \frac{M}{M_B}
  \]
  Where: \( \lambda \): homothetic factor; \( M \): mass of block selected for design and \( M_B \): mass of block tested to obtain infiltration data

- Updating of toe height

- Updating of training walls height:

- Definition of geometry solution according to the height and slope of toe and the dam geometry defined by the designer.

**STEP 3 – Simulation of seepage into toe and under flip bucket**

**STEP 4 – Seepage into drainage layer + assess thickness of drainage layer**

**STEP 5 – Calculation of rip-rap**

**STEP 6 – Calculation of volumes and budget**
section 2.4. They were used to train a neural network that allows computing an estimate of the infiltration flow for any combination of slope and discharge within the considered ranges of variation. This approach is beneficial because it avoids the need to fit a separate expression for each combination of slope and discharge, and provides an estimate for intermediate values. In addition, since the input data have low noise, the training procedure is straightforward. The maximum discrepancy between the numerical results and the estimates of the neural network was 1.26% (Figure 15). This approach is homologous to that followed in a previous work to obtain a general expression to compute the discharge flow in gated spillways on the basis of a numerical modelling campaign [19]. In this case, the library "nnet" [20] was used for the training process.

**STEP 3 – Simulation of seepage into toe and under flip bucket**

- Simulation of seepage into toe and under flip bucket considering non-linear resistance laws [21] and checking of saturation rate:

  - If the following expression is true then go back to step 1 and increase toe height.

\[
GS < 100 \cdot \left( \frac{y_e}{H_t} \right)
\]

Where: GS: maximum saturation rate input; \( H_t \): height of toe and \( y_e \): maximum seepage level under the flip bucket structure.

- If the following expression is true then go to step 4

\[
GS \geq 100 \cdot \left( \frac{y_e}{H_t} \right)
\]

**STEP 4 – Seepage simulation**

- Simulation of seepage into dam body considering non-linear resistance laws [21] and checking of saturation rate, (only for rockfill dam).

  - If the following expression is true then go back to step 1 and increase toe height.

\[
GS < 100 \cdot \left( \frac{y_e}{H_t} \right)
\]

Where: GS: maximum saturation rate input; \( H_t \): height of toe and \( y_e \): maximum seepage level into the dam.

- If the following expression is true then go to step 5

\[
GS \geq 100 \cdot \left( \frac{y_e}{H_t} \right)
\]

**STEP 5 – Seepage simulation**

- Simulation of seepage into drainage layer considering non-linear resistance laws [21] and checking of saturation rate and stability against mass sliding, (only for homogenous dam).

  - If the following expression is true then increase thickness of drainage until unfulfilling the expression

\[
GS < S
\]

Where: GS: maximum saturation rate input and \( S \): saturated percentage of the drainage layer.

  - If the following expression [22] is true then increase thickness of drainage until reaching safety factor value.

\[
F_d = \left( 1 - \frac{y_w}{y_w, sat} \frac{1}{S} \frac{1}{\tan (\phi) \tan (\beta)} \right) \left( 1 + \left( \frac{M \cdot g \cdot (A_B \cdot B_B)}{\lambda} \right) \right)
\]

Where: \( F_d \): safety factor against mass sliding of drainage layer; \( y_w, sat \): saturated specific weight of the material; \( \beta \): dam slope angle; \( \gamma_w \): specific weight of water; \( \phi \): friction angle; \( y_w, dry \): dry specific weight of the material; GS: maximum saturation rate input; \( y_e \): seepage level into drainage layer; \( e_c \): thickness of drainage layer; \( \lambda \): homothetic factor; \( M \): mass of block selected for design; \( g \): gravity acceleration; \( A_B \): lengthwise of block tested to obtain infiltration data and \( B_B \): cross length of block tested to obtain infiltration data.

  - If the following expression is true then go back to step 1 and increase toe height.

\[
H_t > e_c \cdot \cos (\beta)
\]
Where: \( e_t \): thickness of drainage layer; \( \beta \): dam slope angle and \( H_t \): toe height.

- If the following expression is true then go to step 5

\[
H_t \leq e_t \cdot \cos (\beta)
\]

**STEP 5 – Calculation of rip-rap**

- Calculation of diameter of rip-rap as optional superficial erosion protection for toe. This algorithm uses Knauss expression [23] with safety factor 2 to obtain the diameter of stone.

\[
q_i = 0.5 \cdot \sqrt{g} \cdot (d_{rr})^{1.5} \cdot (1.9 + (0.8 \cdot 0.625) - 3 \cdot \text{sen} \alpha )
\]

Where: \( q_i \): seepage flow; \( \alpha \): gravity acceleration and \( d_{rr} \): rip-rap average diameter.

Another expression among those developed in the technical literature could be used by the designer to obtain the diameter of stone.

**STEP 6 – Calculation of volumes and budget**

- Calculation of volumes of materials and final budget.

### 3.3 Implementation

In order to achieve the automation of the previously exposed algorithm an interactive tool was created in Shiny by Rstudio [24-26]. This tool is able to find a design solution, carrying out the process of the algorithm in a few seconds. The software needs several input parameters and gives back the needed output parameters (Table 1) to the complete design of the WSB spillway.

| INPUT | OUTPUT |
|-------|--------|
| Type of dam | Toe slope |
| Downstream slope of dam | Toe height |
| Seepage properties of materials | Saturation rate under flip bucket |
| Discharge flow | Number of blocks |
| Toe water level at downstream | Height of training walls |
| Mass of block | Volumes of materials and budget |
| Width of spillway | Thickness of drainage layer (only for homogeneous dam) |
| Slope of training walls | Saturation of drainage layer (only for homogeneous dam) |
| Maximum saturation rate of porous materials | Rip-rap diameter (optional) |
| Safety factor of toe against mass sliding | |
| Safety factor of drainage layer against mass sliding (only for homogeneous dam) | |
| Cost of materials | |
| Valley shape | |

The tool allows handling these input and output parameters in a friendly way, due to an interactive interface, shown in Figure 16.

It should be noted that there is an option in the tool to carry out an economical optimization of a WSB spillway, regarding the provider's range of blocks and several widths of discharge channel.

### 4 Summary and conclusions

A design procedure for WSB spillways based on numerical modeling of infiltration was presented. This procedure defines the appropriate geometry of the spillway to ensure the stability of the dam against sliding with a sloping toe protection, and to ensure the stability of blocks avoiding water pressure under it.

The design procedure is based on an iterative algorithm coded in R and implemented in an interactive tool based on Shiny.

This tool allows finding the design solution in a few seconds, finding an optimal economic solution from a range of blocks, and this is an important step forward to simplify and popularize the design of WSB spillways.

An accurate knowledge of infiltration flow has been found as the key issue to design WSB spillways, so future research will focus on expanding the ranges of variables studied until now, focused on expand results of slope and flow ranges.

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