# Extended Abstract

## Preliminary design of a shaft spillway of a dam in the Beça River

*Hugo Jonas Ferreira Boavista*

Instituto Superior Técnico, Lisbon

## Abstract

The main objective of the thesis is to elaborate a preliminary design of a shaft spillway of an earth dam located in the Beça River.

The work includes the design of the different elements of a shaft spillway and checking its hydraulic operation safety. In this way, a hydrological study aiming to determine the design flood hydrograph is presented. The study took into account the precipitation and flow rate records collected. The statistical analysis of the collected data was carried out. Using the results from the study, the shaft spillway is designed, including: control structure profile, transition between the control structure and the circular shaft, shaft diameter, bend connecting the shaft to the conduit, conduit and hydraulic-jump stilling basin.

A literature review of each topic is presented, which was the basis for the most significant adopted solutions. At the end of this work, several considerations about the obtained design, the development of the work and the problems identified during the elaboration of the preliminary design are presented.

**Keywords:** Spillway; Shaft; Hydrological study; Hydraulics.

## 1. Introduction

This main objective of the thesis is to elaborate the preliminary design of a shaft spillway of an earth dam located in the Beça River. The hydrological study necessary to establish the design hydrograph was previously developed. This initial study, presented on chapter **2**, was important to determine the design peak flood discharge and the design flood hydrograph. On chapter **3** the dam and the characteristics of the reservoir are briefly described. On chapter **4**, using the design peak flood discharge and the design flood hydrograph determined on chapter **1**, the spillway and the appurtenant structures was designed. On chapter **5**, the conclusions regarding this work and future work recommendations based on the problems identified during this thesis are presented.

## 2. Hydrological study

### 2.1 Location and characteristics of the watershed

The following hydrological study was made for a dam located in the Beça River, near Codessoso, in the Boticas municipality, as shown in Figure 1.

**Figure 1 – Location of the dam**

Some important values regarding the physical characteristics of the watershed were determined (Table 1).

**Table 1 – Characteristics of the watershed**

| Area (km$^2$) | P (km) | Z$_{max}$ (m) | Z$_{min}$ (m) | L$_{river}$ (km) | Z$_{spring}$ (m) | i$_{river}$ | CN |
|---|---|---|---|---|---|---|---|
| 111.08 | 55.2 | 1217 | 709 | 27.65 | 1120 | 0.149 | 60 |

### 2.2. Time of concentration

The time of concentration, $t_c$, of a watershed is the time that it takes to get the contribution of the entire area to the flow rate in its further downstream cross section.

To determine $t_c$, the following formulae were used: USACE (2005), Temez (1978) and Mata-Lima et al (2007) as cited in Nagy et al (2016). The results are shown in Table 2.

Table 2 – Time of concentration (values in h)

| USACE | Temez | Mata-Lima et al | Average |
|---|---|---|---|
| 4.34 | 8.32 | 10.95 | 7.87 |

To proceed with the study, a time of concentration of 8 h was considered. This means that the lag time, as being 60% of $t_c$ according to Mockus (1957) in Woodward (2010), is 4.8 h.

### 2.3. Peak flood discharge using precipitation records

There were 6 rain gauges to analyse the precipitation in the watershed. Thus the watershed was divided into 6 different subareas using the Thiessen method to determine the overall annual maximum daily precipitation for each year of the records collected. A statistical analysis was carried out to estimate the precipitation for a return period of 1000 years, as imposed by Portuguese Dam Safety regulation. Using a Gumbel distribution, that was shown to fit best to the sample, it was estimated that the annual maximum daily precipitation for a 1000 years return period is 155 mm.

The design precipitation corresponds to the precipitation with duration of $t_c$ and a return period of 1000 years. Using the Intensity-Duration-Frequency curves, it was determined to be 101 mm. Three possible design hyetographs were built: hyetograph A (uniform with duration $t_c$), hyetograph B (using alternated blocks and duration $t_c$) and hyetograph C (uniform with duration $2*t_c$).

To calculate the peak discharge the HEC-HMS software, using the Soil Conservation Service (SCS) method, was applied. The highest value simulated by the software to the peak flood discharge was the one corresponding to hyetograph B: $Q = 219\ m^3/s$.

### 2.4. Peak flood discharge using flow rate records

The estimation of the peak flood discharge using flow rate records was based on the records from Vale Giestoso's gauge station. The data collected was converted to the watershed under analysis using a flow transformation proposed by Loureiro (1984).

A statistical analysis, similar to the one applied before, allowed to estimate the instantaneous maximum discharge for a return period of 1000 years. Gumbel distribution proved, again, to fit best to the sample and it estimated $Q=238\ m^3/s$ for an instantaneous maximum discharge for the given return period.

Both estimates (219 and 238 $m^3/s$) were fairly close, which raised the confidence on the obtained results.

## 3. Dam and reservoir characteristics

This preliminary design is aimed for an earth dam 40 m high from crest to talweg, being the talweg at the altitude 710 m, and with a crest length of 76 m. The embankment has a 1/2.3 slope both upstream and downstream. The storage curve of the reservoir is presented in Figure 2. This curve is essential to calculate the flood routing and essential to estimate the outflow through the spillway during a flood.

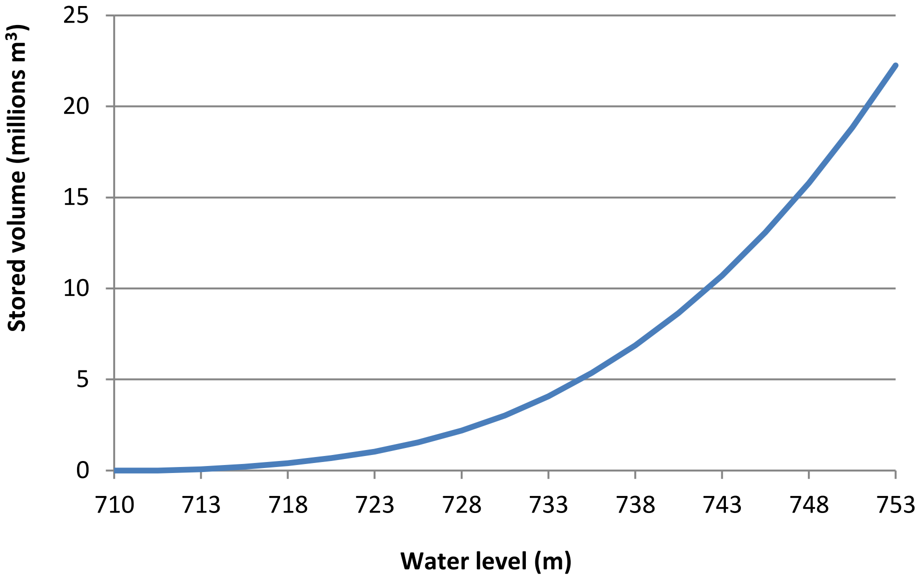

**Figure 2 – Reservoir storage curve**

## 4. Shaft Spillway

### 4.1. Introduction to the subject

The spillway of a dam is responsible for releasing the water surplus that cannot be contained in the reservoir (USBR, 1987) and prevent the dam to get overtopped. In an earth dam, such as this one, this element becomes more important, as overtopping would potentially destroy the dam and put in serious risk the lives of those who live on the valley downstream.

This shaft spillway is more likely to be designed for earth dams than for concrete dams. While in concrete dams spillways are usually placed over or through it, in earth or rockfill dams spillways have to be placed away from the dam to find a suitable foundation. According to Mussali (1969), "shaft spillways are a practical solution in narrow canyons where the abutments rise steeply". On the other hand, if the intention is to provide the spillway with gates to control the outflow, this is not the best solution.

Generally, a shaft spillway with circular crest (also known as morning glory spillway) and its elements can be represented as shown in Figure 3.

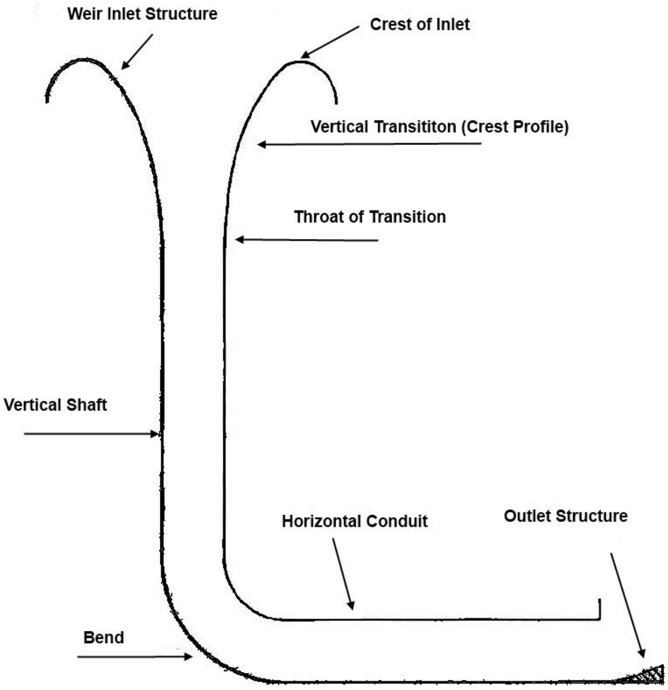

**Figure 3 – Elements of a morning glory spillway (Mussali, 1969)**

The shaft can be either vertical or inclined, depending on the geology and topography of the terrain, hydraulics or economic issues. Downstream of the shaft, there's a bend to connect it to the horizontal conduit. At the end of the spillway there's an outlet structure to dissipate the energy and prevent the flow to excessively erode the riverbed.

The spillway designed in this work is similar to the one presented before. This work includes the preliminary design of the control structure profile, vertical transition, shaft, bend, horizontal conduit and hydraulic jump stilling basin.

### 4.2. Control section

The flow through a shaft spillway can be controlled in 3 different sections (USBR, 1987): crest, throat, or horizontal conduit. During crest control, the flow occurs at atmospheric pressure along the spillway. Its discharge is defined by an equation that depends on $H^{2/3}$. When the relation H/R is about 0.45, the control changes to the throat and the discharge depends on $H^{1/2}$, similar to an orifice control. When that relation H/R approaches 1.00 the control changes to the horizontal conduit and the spillway becomes completely drowned. In this case, the discharge depends on $\left(H - \frac{V^2}{2g}\right)^{\frac{1}{2}}$ as in pipe control. Figure 4 shows how water level on the reservoir varies with increasing discharges and how the different control sections influence the discharge.

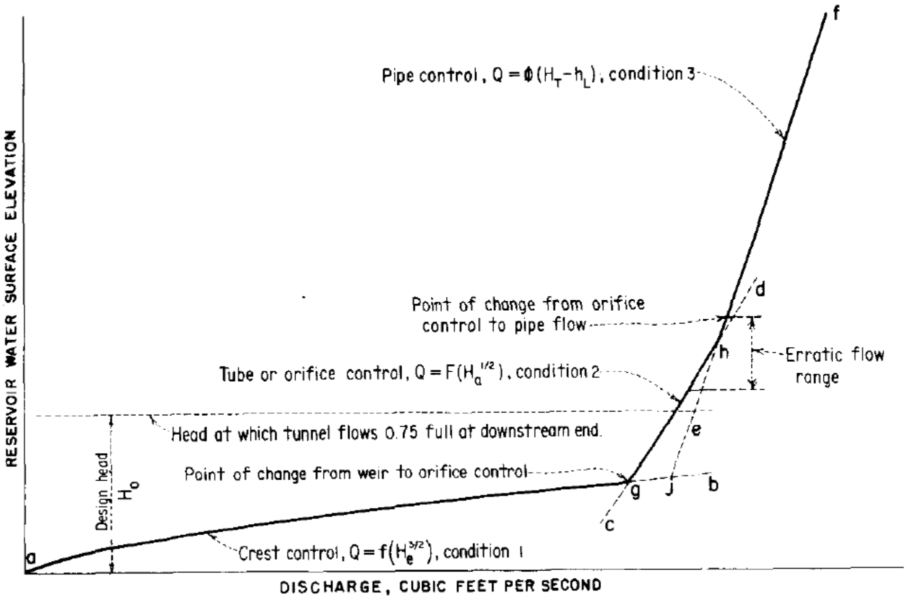

**Figure 4 – Discharge characteristics of a morning glory spillway (USBR, 1987)**

During crest control, the discharge can be increased with relatively small variations on the water level. When the control section passes to orifice or pipe control the water level can escalate with small increment of discharge, which can be potentially catastrophic if the spillway is serving an earth/rockfill dam. Furthermore, according to Fais (2007) changes in control section can be sudden and can cause vibrations due to flow instability. Due to the vulnerabilities of earth dams in case of overtopping, a crest control was adopted to this work.

### 4.3. Design of the crest

To design the crest two different methods to calculate the discharge coefficient, C, were used. One proposed by USBR (1987) and the other proposed by Lazzari (1959).

According to USBR (1987), the coefficient should decrease with higher heads, H, due to the effects of submergence and back pressure caused by a converging flow. On the other hand, in the method proposed by Lazzari (1959) the discharge coefficient increases with higher H. Although the growth of C decelerates, it never reaches a peak during crest control.

It would be expected to have different values of C for low heads than the ones that resulted from both methods. As the relation H/R gets lower, the convergence effect tends to become less important, and therefore the flow would become almost equivalent to the one that occurs on a rectangular section. Since the discharge coefficient for critical flows in rectangular sections is 0.385, that would be the discharge coefficient expected to have for low heads, or, at least, close to that value. Both method results were far from that value, especially when using the method presented by USBR (1987).

The software HEC-HMS was used to simulate flood routing and test multiple solutions. It was adopted a crest with 7 m radius and the method given by Lazzari (1959) to estimate C. The simulation made resulted in a maximum discharge Q=161 $m^3$/s and a maximum elevation of H=1.6 m.

### 4.4. Freeboard

To determine the freeboard, an estimation of the peak flood discharge for a 5000 years return period using the precipitation records was made. Using the same method used to estimate the peak flood discharge for a 1000 years return period and a uniform hyetograph, this estimation resulted in a flow rate 184 $m^3$/s and H=1.80 m. Above this value, a clearance of 1.20 m was adopted, which made a total freeboard of 1.40 m. From the total freeboard it was possible to establish the full reservoir level (FRL) and the maximum water level (MWL). Those values are presented in Table 3.

**Table 3 – Free board, talweg, FRL, MWL and top of the dam levels (values in m)**

| Free board | Talweg | FRL | MWL | Dam |
|---|---|---|---|---|
| 1.40 | 710.00 | 747.00 | 748.60 | 750.00 |

### 4.5. Vertical transition

The vertical transition shape was set following the recommendation from USBR (1987) to use a layout that would correspond to the lower nappe of a jet with the same head and flow rate flowing over an aerated sharp-crested circular weir to avoid low pressures that could cause cavitation.

### 4.6. Throat

The throat was designed using the formula (1) given by USBR (1987) to determine the minimum shaft's radius:

$$R_{min} = 0.275\frac{Q^{0.5}}{H^{0.25}}$$

The estimated minimum radius was 3.10 m. A 3.50 m radius for the shaft was adopted.

### 4.7. Bend

The bend is a critical spot due to high velocities, strong flow deflexion, depressions on the surface of the inner part of the bend, strong impact from the falling water and vibrations. To prevent damages, Mussali (1969) recommends a smooth surface with the least construction joints. In most cases, the bend is circular but recommendations to its radius are scarce. In any case, it should be able to allow the passage of tree trunks. Other studies suggest other types of bends, such as multiple radius bends. A single radius bend with R=10 m was adopted.

### 4.8. Horizontal conduit

Generally, the flow in the horizontal conduit should occur on free surface. This prevents the structure from damages caused by high pressures or hydraulic jumps against its surface (Pinheiro, 2005). These damages represent a huge risk in case of earth dams. Different recommendations were found about how full should run the conduit. In this work, it was adopted the most conservative recommendation that states that the section should be 2/3 full (Genovez and Genovez, 2000). It was used Colebrook-White's formula in order to guarantee this condition and to determine the conduit's declivity. In this conduit it was also adopted the same radius used in the shaft (R=3.5 m). These premises led to a declivity and a specific energy on steady flow as shown in Table 4.

**Table 4 – Conduit slope and specific energy on steady flow**

| Q ($m^3/s$) | i | H (m) |
|---|---|---|
| 160.6 | 0.0007 | 6.47 |

In the last 15 m there is a smooth transition to a rectangular cross section on the bottom half of the conduit, to adapt for the outlet and to the energy dissipation structure. Its total length is about 170 m.

### 4.9. Energy dissipation structure

A type IV hydraulic jump basin, presented by USBR (1987), was used to dissipate the flow energy and prevent erosion on the natural channel. It was assumed that in the final section of the conduit the flow has already reached the stage of steady flow. Although this assumption may not be the most plausible scenario, it was considered due to lack of information to estimate the head losses in the bend and, therefore, to estimate the free surface profile.

## 5. Conclusions and future work

This work main objective was to make a preliminary design of a shaft spillway for an earth dam in the Beça River.

The close results obtained from the hydrological study showed that the hydrological data was relatively reliable.

For earth dams, the shaft spillway should be designed to operate in free surface flow all along the spillway structure to have a reasonable safety factor against overtopping, and to avoid vibrations during changes in control sections.

Considering the inefficiency of the tested methods to estimate the control structure discharge coefficient for low heads, further research on this matter is recommended. It was also observed that, despite being a critical spot, few studies are available and no regulation exists regarding how the bend should be designed. Due to its high/low pressures, vibrations, flow speed and turbulence it is also recommended that this subject should be further investigated.

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