# Design of concrete stepped overlay protection for embankment dams

K.H. Frizell
*Research Hydraulic Engineer, U.S. Bureau of Reclamation, Denver, Colorado, USA*

*Phone: (303) 445-2144; Fax: (303) 445-6324; E-mail: kfrizell@do.usbr.gov*

Jorge Matos, Ph.D.
*Lecturer, Instituto Superior Tecnico, Technical University of Lisbon, Portugal*

Antonio N. Pinheiro, Ph.D.
*Assistant Professor, Instituto Superior Tecnico, Technical University of Lisbon, Portugal*

ABSTRACT: Many embankment dams have been considered unsafe due to inadequate spillway capacity and predicted overtopping during extreme flood events. In recent years hydraulic research has greatly advanced the concept of embankment protection systems. Based on the available experimental data gathered on laboratory and near-prototype flumes, the authors address the design of stepped overlays for embankment dams. Results show that properly designed stepped overlays are inherently stable, critical for embankment dam. Also, a considerable amount of energy is dissipated by flow over the steps formed by the block surface.

Topics discussed include block shape, stability, air entrainment and flow resistance in skimming flow on stepped spillways. Remarks on the hydraulic design are included with the projected cost-effectiveness of a tapered concrete block system over embankment dams.

## 1 INTRODUCTION

Safe and economical methods to increase the discharge capacity of embankment dams has led to extensive research into previously unacceptable or non-conventional methods for passage of flood flows over the downstream slope of embankment dams. Any failure or instability in the protective embankment system could cause a catastrophic failure of the entire dam during an overtopping event. Therefore, laboratory and near-prototype facilities have been used to investigate the hydraulic conditions on stepped surfaces. The facilities discussed were located in Reclamation's Water Resources Research Laboratory in Denver, Colorado, Colorado State University (CSU) in Fort Collins, Colorado, and the National Civil Engineering Laboratory (LNEC) with cooperation of the Technical University of Lisbon in Lisbon, Portugal. The results from these various laboratory facilities, with variable slopes from 1V:2H to 1V:4H and 0.8V:1H, and near-prototype slope of 1V:2H, have increased the knowledge of stepped spillway performance. Of particular interest for this paper is the verified performance (Frizell, 1997) of a tapered concrete block system (U.S. patent No. 5544973) that will protect the downstream slope of embankment dams during flow events.

## 2 LARGE-SCALE TEST FACILITY AND BLOCK DESCRIPTION

The outdoor overtopping facility, located at CSU, was sized to be similar in height to a typical embankment dam in need of rehabilitation. The facility consists of a concrete headbox, chute, tailbox, and sump with a pump. The concrete chute is on a 1V:2H (26.6 degree) slope and has a height of 15.24 m. The maximum width of 3 m was reduced to a width of 1.5 m to increase the unit discharge capacity to 3 $m^3/s/m$ for the tapered block testing.

Reclamation's laboratory data showed that the ability of the blocks to relieve the uplift pressure, combined with the impact of the water on the block surface, made the blocks inherently stable. Based upon these laboratory studies, the tapered, overlapping concrete blocks were designed and constructed for the large-scale tests (Figure 1). The blocks were 37.5-cm-long and 6.4-cm-high with a maximum thickness of 11.4 cm. Vents, formed in the overlapping portion of the block, aspirate water from the filter layer. The block thickness was minimized to test a "worst case" scenario and a 0.3-m-wide block had a dry weight of 17.4 kg. A minimal thickness of 5 cm at the upstream end of the block was required to maintain the integrity of the concrete and allow proper forming of the block.

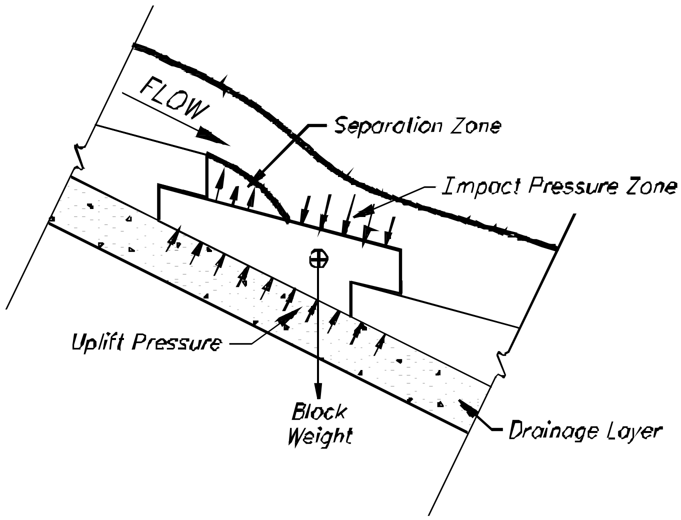


Figure 1. Block shape and force diagram for the tapered concrete block system. Vents are located in the overlapping portion of the block.

The blocks were placed over 15.24 cm of free draining, angular, gravel filter material. The filter material and thickness were designed according to Reclamation design guidelines. The gravel filter was placed on the concrete floor with angle iron (with a gap above the floor to allow free discharge underneath) placed every 1.8 m up the slope to prevent sliding of the gravel. A wooden strip was installed along each wall to easily screen the gravel filter and to prevent failure along the wall contact during operation. A combination of 61.0-cm and 30.5-cm-wide blocks was placed on the "embankment" shingle-fashion from the slope toe with no continuous seams in the flow direction.

At the crest of the structure, a small concrete cap was placed to transition from the flat approach to the first row of blocks. At the toe of the concrete slope a fixed concrete end block supports the blocks up the slope.

### 2.1 *Block design*

The most stable block shape on a 1V:2H slope is the 15 degree tapered block (Figure 1) (Frizell, 1991). The block design is based upon keeping the difference between the top slope and the embankment slope constant for a given embankment dam slope. Therefore, when designing a block to provide effective aspiration, a difference between block and embankment slope of about $11^{o}$ has been found to work fairly well. Inappropriate block slopes may produce instabilities by providing an overly large low pressure zone or normal forces that are too small.

A general guideline also keeps the ratio of the step length exposed to the flow to the step height between four and six (Baker *et al.*, 1994). This assures that the step height and tread length proportions are adequate to produce the correct jet impingement on the step tread. If the step height is chosen to match that of our testing, 6.35 cm, then the tread length should be between 25.4 to 38.1 cm. This horizontal tread length is then used to determine the length of the block surface along the embankment slope.

The percent of the vertical step face area occupied by the vents should be 2.8% (Baker *et al.*, 1994). Proper sizing of the port area limits the uplift pressure developed in the filter layer. The vents must be sized so that the filter material underneath will not be transported through the ports.

The block thickness is determined from the stability analysis in the following section.

### 2.2 *Block Stability*

The question of stability of the protective system is the most critical for an embankment dam. The block geometry optimizes the hydraulic forces to produce downward impact pressure and aspiration of sub-grade pressures.

The stability of the block system has been analyzed as a function of the total forces acting on individual blocks down the slope (Figure 1). Pressure data were gathered to compute the magnitude of the forces acting on the block surfaces and in the underlying filter. For discharges producing skimming flow, impact pressures increase to a maximum about 44 steps down the slope, then decrease due to aeration effects. The filter pressures show a gradual increase over about the top 40 steps, indicating a buildup of flow in the filter near the top of the slope. At about 45 steps down the slope, aspiration increases and the filter pressures quickly decrease to an average uplift of about 3 cm at the toe of the slope for all flow rates.

Block weight and pressure yield a net downward or positive force normal to the slope. The uplift pressure in the filter material underneath the block and the low-pressure zone created by the block offset act in an upward (negative) direction tending to lift the blocks from the embankment surface. Aspiration ports in the vertical face of the block limit the uplift forces by venting the filter layer to the low-pressure separation zone. The net force/meter of block width was obtained by integration of the pressure profile on the step tread and the measured filter layer pressure. The submerged block weight of about 5.9 kg was not included in the analysis so that a block of any weight could be easily designed. The analysis also did not include the additional stability provided by the block overlap, which creates a beneficial interlocking affect.

This block shape was successfully tested in the large-scale facility for unit discharges up to 3 $m^3$/s/m. Net downward forces were obtained for this block shape and filter indicating a stable overlay for a 1V:2H slope for the range of critical depth to step height ratios tested of 3.36 to 15.21 (Frizell, 1997). These results indicate no decrease in block system stability with increasing unit discharge.

## 3 AIR ENTRAINMENT AND ENERGY DISSIPATION

### 3.1 *Definitions*

The local air concentration $C$ is defined as the time averaged value of the volume of air per unit volume. The equivalent clear water depth is defined as

$$d = \int_0^{Y_{90}} (1 - C)\, dy \tag{1}$$

where y is measured perpendicular to the spillway surface and $Y_{90}$ is the depth where the local air concentration is 90 percent. A depth averaged mean air concentration for a fluid is then defined as

$$d = (1 - C_{mean})\, Y_{90} \tag{2}$$

The average water velocity $U_w$ is defined as

$$U_w = \frac{q_w}{d} \tag{3}$$

### 3.2 *Air entrainment*

In addition to confirming the stability of the block system, air concentration and velocity data were collected in the CSU overtopping facility to use in defining the flow resistance and energy dissipation characteristics of the overtopping protective system. A conclusion from this study was that the air concentration distribution throughout depth downstream from the point of inception of air entrainment was similar over both smooth and rough surfaces (Ruff and Frizell, 1994). The mean air concentration from the CSU tests was 0.34. The similarity between stepped and smooth air concentration profiles has been confirmed on steep stepped chutes (Matos and Frizell, 1997) and on flat stepped cascades (Tozzi et al. 1998). The profiles measured experimentally at CSU for a 1V:2H stepped slope were compared to a profile of uniform self-aerated flow over a smooth chute of identical slope computed using a model for the air concentration distribution (Wood, 1985) and a formula for the estimation of the uniform mean air concentration (Hager, 1991). The mean air concentration computed for uniform flow on a smooth chute was 0.41.

Although the measured profiles were similar near the toe of the slope, uniform flow conditions might not have been attained down the stepped chute. Figure 2 shows the growth of the mean air concentration down stepped chutes typical of embankment dams as a function of the normalized distance $s$ ($s$ = $(L-L_i)/d_i$), where $L$ is the distance measured along the chute, $L_i$ is the distance from the inception point of free-surface aeration, and $d_i$ is the flow depth at the inception point. The formulae presented by Chanson (1994) for the estimation of the parameters $L_i$ and $d_i$ have been applied as they were developed for chute slopes from 26.6 to 53.1 degrees. From Figure 2 it can be seen that the data of Gaston (1995) at CSU are similar to the data of Boes and Hager (1998) on a similar sloping stepped chute. These data approach, but do not reach, the mean air concentration estimated for a smooth chute of identical slope ($C_{mean}$ = 0.41 for $\alpha$ = 26.6 degrees). Therefore, it appears that uniform flow was not reached in both experimental tests. Figure 2 also shows that the mean air concentration at the inception point is significant at $C_{meani} \approx 0.25$. This is due to free-surface deformation transporting entrapped air along with the flow but $L_i$, $d_i$ , and $C_{meani}$ may be slightly be overestimated (Matos et al. 1999).

The data of Gaston (1995) and Boes (1999) fit reasonably well to the equation

$$C_{mean} = 0.23 + 0.017\, s^{0.46} \tag{4}$$

which was obtained for experimental values of $s$ lower than 80.

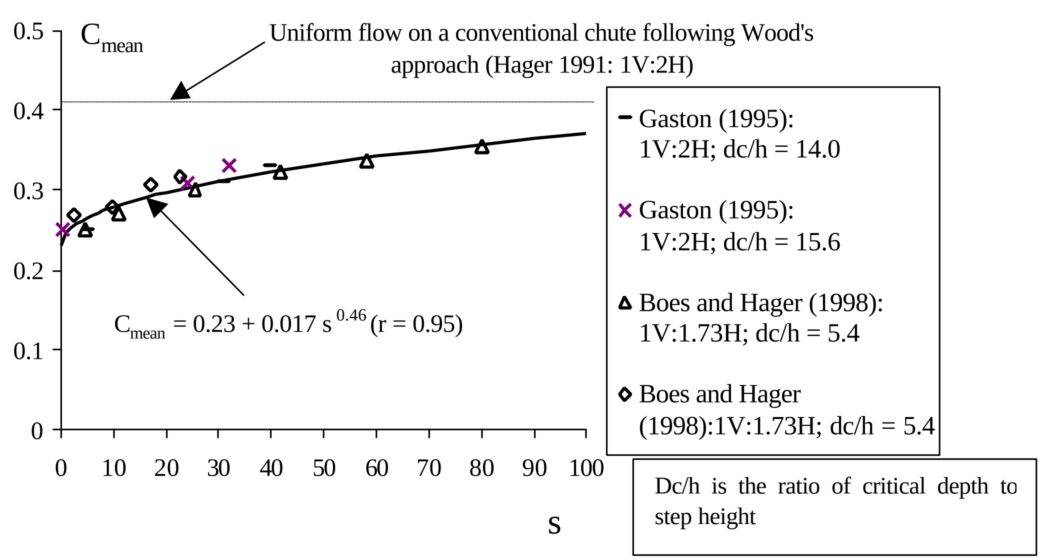


Figure 2. Mean air concentration as a function of the normalized distance down the slope.

3.3 *Flow resistance*

In skimming flows over stepped spillways, the friction factor can be written as (Chanson 1994)

$$f = f\left(\frac{k}{D_h}, \quad \sin a, \quad C_{mean}\right) \tag{5}$$

where $k$ is the step roughness height and $D_h$ the hydraulic diameter based on the equivalent clear water depth. For stepped spillways of identical slope, $f$ becomes only a function of $k/D_h$ and $C_{mean}$. Figure 3 presents the experimental results of $f$ obtained after a reanalysis of the data collected by Tozzi (1992), Gaston (1995) and Rice and Kadavy (1996) estimated from

$$f = \frac{2\, g \sin a \; D_h}{U_w^2} \tag{6}$$

The experimental data presented by Boes (1999) is also included in figure 3. Although the final mean air concentration may not have been reached, the friction (energy) slope is expected to be nearly parallel to the pseudo-bottom (bed slope), thus using Eq. 6 seems acceptable. Tozzi (1992, 1994) estimated the friction factor of air flowing in a closed conduit, with roughness elements designed to simulate those on a 26.6-degree sloping chute. For identical $k/D_h$, the friction factor computed using the data of Rice and Kadavy for a 22 degree stepped chute are higher than those from the other experiments. This higher friction factor may be a result of no air entrainment in the experiments (Matos, 1997), model scale effects, or non-uniform flow.

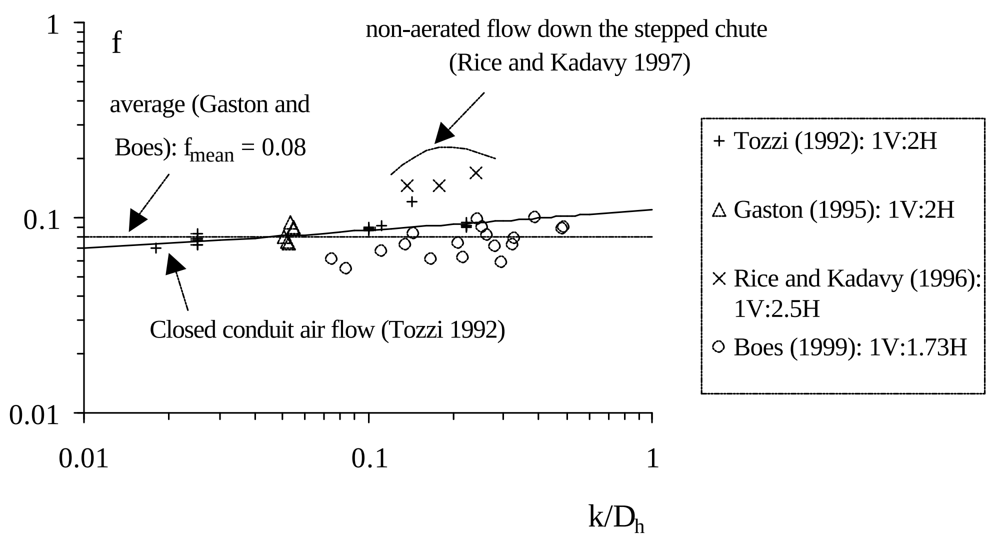


Figure 3. Friction factor as a function of ratio of step roughness to hydraulic diameter for experimentally obtained velocities and air concentrations.

Figure 3 shows that the $f$ values from Gaston fit well to the formula of Tozzi (1992, 1994), whereas the data of Boes (1999) are lower. Reasons might be the effect of the significant mean air concentration (i.e., C ~ 0.4) and a slightly steeper slope for most of the data of Boes. The relative roughness $k/D_h$ does not appear to have a significant influence on $f$, with an average $f$ of 0.08 for stepped spillways over typical embankment dam slopes, in the air-water gradually varied flow region.

## 4 HYDRAULIC DESIGN CONSIDERATIONS

### 4.1 *Flow properties at inception point*

The location of the inception point and the respective flow depth can be estimated by the formulae proposed by Chanson (1994, p. 78). With regard to the mean air concentration at the inception point, a value of about 0.23 can be used (Eq. 4).

### 4.2 *Mean air concentration down the stepped chute*

Eq. 4 can be used to estimate the mean air concentration at the downstream end of the spillway. In case of high values of $s$ (e.g., $s > 100$), where a quasi-uniform fully aerated flow might be attained at the spillway toe, the mean air concentration can be assumed equal to that obtained in a smooth chute of identical slope (see e.g., Hager 1991).

### 4.3 *Training wall height*

The design of the training walls should take into account free-surface aeration. The estimation of the characteristic depth $Y_{90}$ requires the knowledge of the mean air concentration $C_{mean}$ (Eq. 4) and also of the equivalent clear water depth, $d$ (Eq. 1). The above parameters can be estimated from Eq. 4 and 6, for $f = 0.08$.

### 4.4 *Residual energy*

The specific energy at the spillway toe (residual energy) can be estimated by Chanson (1994, p. 103), where $f$ can be assumed equal to 0.08. It is important to note that the above formula is only precise if quasi-uniform flow conditions are reached at the toe of the spillway.

### 4.5 *Potential for cavitation damage*

To the authors' knowledge, cavitation damage has not occurred during operation of stepped spillways. Stepped block protection systems have been successfully used on flat slopes on several Russian dams with design discharges up to 20 $m^2/s$ (Pravdivets et al. 1980). Prototype tests have also been conducted for unit discharges up to 60 $m^2/s$ on a special test chute at the Dneiper hydroplant (Pravdivets and Bramley 1989). However, if the stepped chute is designed for significantly higher unit discharges, the likelihood of cavitation should be investigated.

## 5 NON-CONVENTIONAL SPILLWAYS CHARACTERISTICS

Three types of non-conventional spillways founded on the downstream slope of earth dams were considered; Type I - Reinforced concrete channel, Type II - Gabions stepped channel, and Type III - Pre-cast concrete blocks stepped channel. From a hydraulic point of view, the type I spillway is similar to chute spillways founded in one of the dam abutments. However, if founded on the embankment, some special precautions must be taken in the design of the slab joints and in the drainage layer (Albert *et al.*, 1992).

Gabions forming stepped channel spillways (type II) increase the energy dissipation relative to an impervious stepped channel. Flow through the gabions increases the energy dissipation. Peyras *et al*. (1991) showed that using of gabions in stepped channels with nappe flow allows a reduction in the energy dissipation basin length up to 30 percent compared to conventional smooth chute spillway basins. Peyras *et al*. presented design criteria for gabion overflow structures.

The type III spillway was developed in the former USSR (Pravdivets and Slissky, 1981). Its fundamental characteristic is the use of wedge-shaped pre-cast concrete blocks. The blocks are used with a drainage layer, which filters the seepage flow and protects the subsoil from flow erosion. The blocks are inherently stable due to the hydrodynamic forces generated by the skimming flow (Baker *et al*., 1994; Frizell, 1997). To improve the block stability and the performance of the drainage layer, drainage holes are made in the blocks, assuring, together with the drainage layer, that uplift forces are negligible. The channel is lined with rows of blocks, placed tightly, in shingle-fashion from the downstream toe with no longitudinal joints aligned.

### 5.1 *Design criteria and cost estimate*

To rapidly evaluate the economic advantages of the construction of non-conventional spillways just described, Relvas (1997) developed a computer program for conducting preliminary designs of non-conventional spillways. The program computes the main characteristics of several solutions, with different channel widths for each spillway type. With input of a set of unit costs for the main types of works included in the spillway's construction, the program also computes the respective cost estimates, following an iterative cycle converging to minimum cost.

### 5.2 *Case studies*

The costs of non-conventional spillways founded on the downstream slope of embankment dams were compared with the costs of conventional spillway solutions. Following are brief descriptions of three Portuguese dams that were selected for comparison (Table 1):

- Foz do Guadiana dam is 22 m high with an ogee crest and chute spillway designed for 24 $m^3/s$.
- Enxoé dam is 21 m high with a non-conventional stepped chute spillway designed for 42 $m^3/s$. It includes an 8-m-wide horizontal free flow control structure followed by a 68.5-m-long stepped concrete rectangular channel of the same width, adjacent to downstream slope of the dam. The steps are 1.50 m high. The first spillway reach is followed by a 50-m-long stepped-trapezoidal-channel lined with Reno mattresses forming 1 m high steps. The adoption of a stepped spillway was intended to eliminate a downstream energy dissipation structure (LNEC, 1996).
- Ribeira de Oeiras dam is 27 m high with a chute spillway with an ogee crest designed for 291 $m^3/s$.

Table 1. - Minimum cost estimates of non-conventional spillways for the three case studies.

| Dam | Spillway costs (1000 EUR) and percentage differences to conventional solution | | | | | | |
|---|---|---|---|---|---|---|---|
| | Conventional | Type I | | Type II | | Type III | |
| Foz do Guadiana | 465 | 236 | -49% | 201 | -57% | 160 | -66% |
| Enxoé | 512 | 321 | -37% | 310 | -39% | 181 | -65% |
| Ribeira de Oeiras | 1415 | 1527 | +8% | 1951 | +38% | 710 | -50% |

## 6 CONCLUSIONS

Extensive test programs have shown that a properly designed stepped overlay is inherently stable due to the combined effect of the impact of the flow on the step surfaces and the ability of the stepped overlay to relieve the uplift pressure. In quasi-uniform flow, the mean air concentration on stepped surfaces is expected to approach that of smooth surfaces of about 0.4 and the friction factor, possibly affected by air concentration, is estimated to be 0.08 for typical embankment slopes. Training wall heights and residual energy can be designed from recommendations presented. Using tapered concrete blocks on the downstream slope of earth dams to replace conventional works will decrease the cost by an average of about 60 percent. Tapered blocks were cost competitive with conventional methods when other non-conventional methods were not. A small dam in the U. S. to use as a demonstration site for the tapered block system is still being pursued.

## 7 ACKNOWLEDGMENTS

The assistance of Mr. Robert Boes (*ETH Zurich, Switzerland*) in providing experimental data to the second author is gratefully acknowledged.

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