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# DECREASING SCOUR POTENTIAL DOWNSTREAM OF OVERTOPPING DAMS USING CREST MODIFICATIONS

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The Eagle Nest Dam is a 43m high concrete arch dam near Eagle Nest, New Mexico USA. During the probable maximum flood (PMF), the dam will be overtopped resulting in significant anticipated scour of the dam abutments and toe. The approach that was followed to reduce the risk of scour was to break up the overtopping jet. Two crest modifications were tested to determine relative effectiveness. A physical hydraulic model study of the dam was performed. Pressures measured in the model compared reasonably well with those that could be calculated theoretically. The study showed that the crest modifications could reduce the average dynamic pressure coefficient but that the fluctuating dynamic pressure coefficient remained relatively unchanged. The total reduction of pressure associated with the crest modifications is anticipated to reduce scour of the dam foundation.

***Key Words :*** *scour, dam, overtopping, physical hydraulic model, flow splitters, high velocity jet*

## 1. INTRODUCTION

The Eagle Nest Dam is a 43m high concrete arch dam. During the probable maximum flood (PMF) event the dam will be overtopped. Theoretical scour estimates for the PMF event are on the order of 18m to 25m below the bedrock ground surface at the toe of the dam, which could result in an uncontrolled release. To help select appropriate remedial measures, a physical hydraulic model study of the dam was performed. The model was used to:

- verify theoretical pressure estimates to determine the amount of erosive capacity reduction following crest modification
- identify a preferred crest modification to remediate scour

The results of this study are presented herein.

## 2. BACKGROUND INFORMATION

The Eagle Nest Dam is located on the Cimarron River near the town of Eagle Nest, New Mexico USA. The dam has one spillway excavated into the bedrock on the left abutment with the discharge capacity of approximately 170m$^3$/s. An abandoned train tunnel exists on the right abutment that would also witness flow during a PMF event.

During a PMF event, a peak flow of approximately 1800m$^3$/s of water is expected to discharge from the dam, 1630m$^3$/s of which will overtop the crest. The height of water in the reservoir behind the dam is expected to be approximately 4m above the crest of the dam (Powledge et. al, 1999).

## 3. THEORETICAL SCOUR PREDICTIONS

Two methods were used to determine the extent of scour at Eagle Nest Dam under PMF conditions. These were:

- Bollaert's Comprehensive Fracture Mechanics (CFM) and Dynamic Impulsion (DI) models (2002), and
- Annandale's Erodibility Index Method (EIM) (1995, 2006).

The first method, by Bollaert, relates erosive capacity in terms of pressure fluctuations, while the second method, by Annandale, describes erosive capacity in terms of unit stream power. Bollaert's method utilizes a dynamic pressure coefficient that accounts for variations in the average and fluctuating dynamic pressures. This coefficient has also been applied to Annandale's method to estimate the decay of stream power as a function of plunge pool depth as well as to incorporate the effects of air entrainment into the jet. This coefficient is described below and will be used for comparison with the physical hydraulic model study results.

Recent research by Castillo (2007) and Ervine, Falvey and Withers (1997) regarding the effects of jet break up on the average dynamic pressure and fluctuating dynamic pressure, respectively, has been combined with that by Bollaert (2002) to form the total dynamic pressure coefficient. This may be written as:

$$C_t = C_p + \Gamma \cdot RF \cdot C_p' \qquad (1)$$

Where:
$C_p$ = average dynamic pressure coefficient (Castillo, 2007) (**Fig. 1**).
$C'_p$=fluctuating dynamic pressure coefficient (Bollaert, 2002) as shown in (**Fig. 2**).
$\Gamma$ = amplification factor for resonance that can occur in close-ended rock joints applied to $C'_p$ (Bollaert, 2002). (This cannot be accounted for in the physical model measurements and has therefore been set = 1 to allow comparison).
*RF* = dynamic pressure reduction factor dependent on the degree of jet breakup based on research by Ervine, et. al. (1997) (Annandale, 2006) (**Fig. 3**).

For the calculation of the total dynamic pressure coefficient it is necessary to determine the degree of jet break-up. The degree of jet break up is determined by the ratio of the jet trajectory length (L) to the jet break up length ($L_b$). The length of the jet, calculated by Annandale (2006), may be expressed as:

$$L = \int_0^x \sqrt{1 + \left[ \tan(\theta) - \frac{2x}{4\left(\frac{v^2}{2g}\right)\cos(\theta)^2} \right]^2} \cdot dx \qquad (2)$$

Where:
$x$ = horizontal impact distance (m)
$\theta$ = issuance angle
$v$ = initial issuance jet velocity (m/s)

Two separate equations to calculate the jet break up length were investigated. These are the methods by Horeni (1956) and by Ervine, Falvey and Withers (1997). The two equations are provided below.

$$L_b(Horeni) = 6 \cdot q^{0.32} \qquad (3)$$

Where:
q = the unit discharge (m2/s).

$$L_b(Ervine) = \frac{1}{2} \cdot d \cdot Fr^2 \cdot \frac{\frac{-1}{2} \cdot C + 1 + \frac{1}{2} \cdot (C^2 + 4 \cdot C)^{\frac{1}{2}}}{C} \qquad (4)$$

Where:
$d$ = issuance jet depth/thickness (m).
$Fr$ = issuance Froude number
$C = 1.07 \cdot T_u \cdot Fr^2$. where Tu is the issuance turbulence intensity.

Theoretical average and fluctuating pressure coefficient estimates for Eagle Nest Dam using these equations and **Fig.1, 2** and **3** are presented in **Table 1**.

## 4. PHYSICAL HYDRAULIC MODEL

The Eagle Nest Dam physical hydraulic model was constructed at a 1:24 scale, which was deemed adequate to allow for representative measurement of the average and root mean square (RMS) pressures. Nine pressure transducers, sampling at a rate of 100Hz, were placed at the toe of the dam, the abutments and downstream of the jet impact location to record pressures associated with the overtopping jet over a 30 second period for each test.

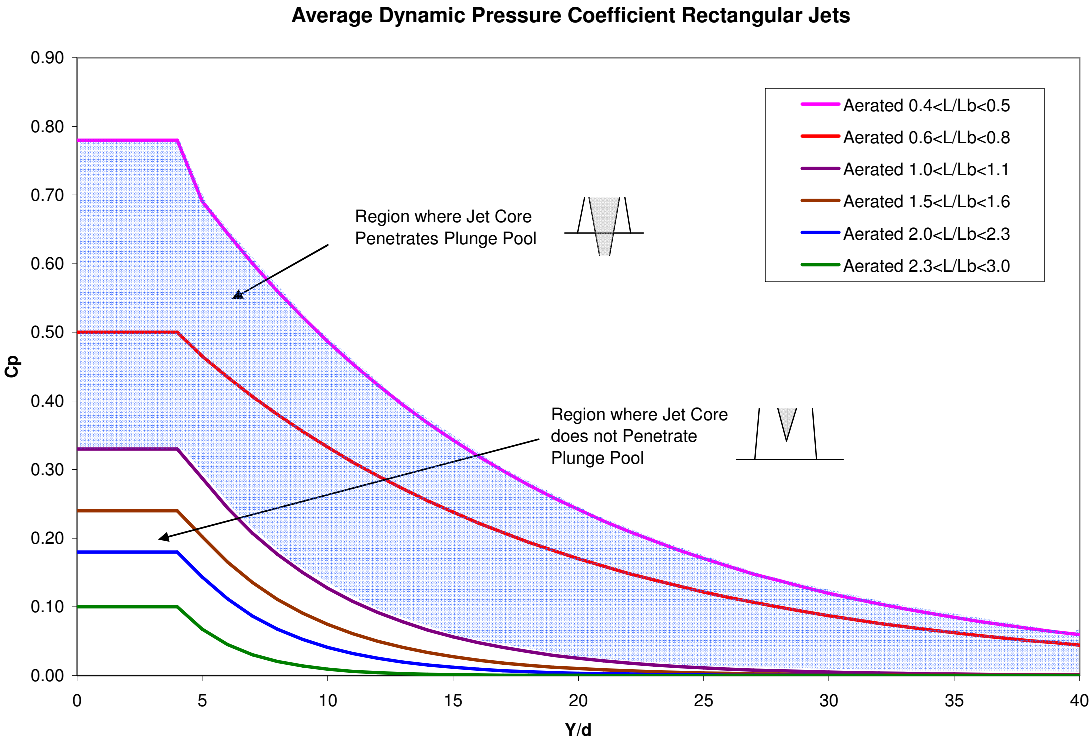

**Fig. 1** Calculation of Cp from Castillo (2007)

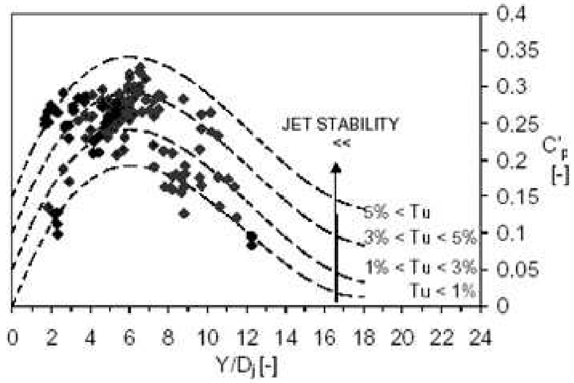

**Fig. 2** Determination of C`$_p$ based on research by Bollaert (2002).

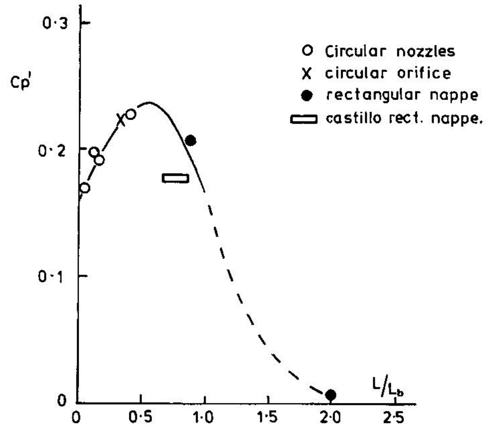

**Fig. 3** Relation of C`$_p$ to break up length ratio (L/L$_b$) based on research by Ervine et. al (1997).

The scaled flow discharges used in the test equaled 100%, 50% and 25% of the PMF magnitude. Only the results for the 100% PMF have been provided for this paper. For each test the average, C$_p$, and fluctuating (RMS), C'$_p$, pressure coefficients were calculated for comparison with the theoretical pressure coefficients.

The average dynamic pressure coefficient from the model data can be calculated as:

$$C_p = \frac{\frac{P}{\gamma} - Y_p}{\frac{V^2}{2g}} \approx \frac{\frac{P}{\gamma} - Y_p}{H} \qquad (5)$$

Where:
$H$ = head differential from reservoir to tailwater (m)
$P$ = measured pressure (Pa)
$V$ = impact velocity (m/s)
$Yp$ = plunge pool (tailwater) depth (m)

The fluctuating dynamic pressure coefficient can be calculated as:

$$C_p^{'} = \frac{\sigma}{\frac{V^2}{2g}} \approx \frac{\sigma}{H} \tag{6}$$

Where:
$\sigma$ = standard deviation of the dynamic pressure head variation (m).

### (1) Comparison of Modeled and Theoretical Results – Original Crest

The first series of model tests focused on measuring pressures for the original (current) dam layout for comparison with the theoretical pressure estimations. The original crest of the dam is essentially a walkway across the crest that is 2.7m wide and has 1m high posts on the upstream and downstream side. **Fig. 4** shows the flow for the original dam crest configuration at 100% of the PMF.

Note that the overtopping jet impacts very close to the toe of the dam, which may pose a stability issue for the dam should a scour hole form in that region. Additionally, the transparency of the overtopping jet suggests that it is relatively intact and has a high erosive capacity.

Finally, high velocity discharges down the abutments into the tailwater at the toe of the dam were observed (**Fig. 5**). Flow from each abutment, converging at the dam toe, resulted in violent turbulent mixing against the dam face and toe. This phenomenon was not accounted for in the theoretical analysis and is expected to increase the erosion potential of the overtopping jet.

**Table 1** compares the measured pressure coefficients for the original crest when the discharge equals 100% of the PMF and the theoretically calculated values. Values are provided for the center (dam toe), right abutment and left abutment. In general, model values agrees relatively well with the pressure coefficients calculated using the Ervine et al.(1997) equation for determining jet break-up length and the Castillo (2007) (**Fig. 1**), Bollaert (2002) (**Fig. 2**) and Ervine et al. (1997) (**Fig. 3**) relationships for determining average and fluctuating dynamic pressure coefficients as expressed by Equation (1).

**Fig. 4** Original crest configuration for 100% PMF

**Fig. 5** High velocity flows down abutments causing turbulence at the dam toe for PMF with original crest configuration. Dam constructed of plexiglass: view is from behind dam.

**Table 1** Theoretical and Measured Dynamic Pressure Coefficients for Original Crest

| 100% PMF | | | | |
|---|---|---|---|---|
| Location | | Theoretical | | Measured |
| | | Ervine Eqn. | Horeni Eqn. | Original Crest |
| Center | $C_p$ | 0.240 | 0.100 | 0.212 |
| | $C'_p$ | 0.036 | 0.017 | 0.034 |
| Left Abutment | $C_p$ | 0.500 | 0.200 | 0.618 |
| | $C'_p$ | 0.115 | 0.017 | 0.229 |
| Right Abutment | $C_p$ | 0.310 | 0.100 | 0.301 |
| | $C'_p$ | 0.084 | 0.017 | 0.291 |

## (2) Crest Modifications

Two separate crest modifications were tested to determine their effects on anticipated scour of the dam foundation: these are the Roberts Crest and the Falvey Crest.

The Roberts Crest shape is based off the Roberts splitter design developed in South Africa (**Fig. 6**). The crest consists of several splitters that sit above a horizontal lower lip. Part of the overtopping flow impacting the splitters is projected horizontally in a downstream direction.

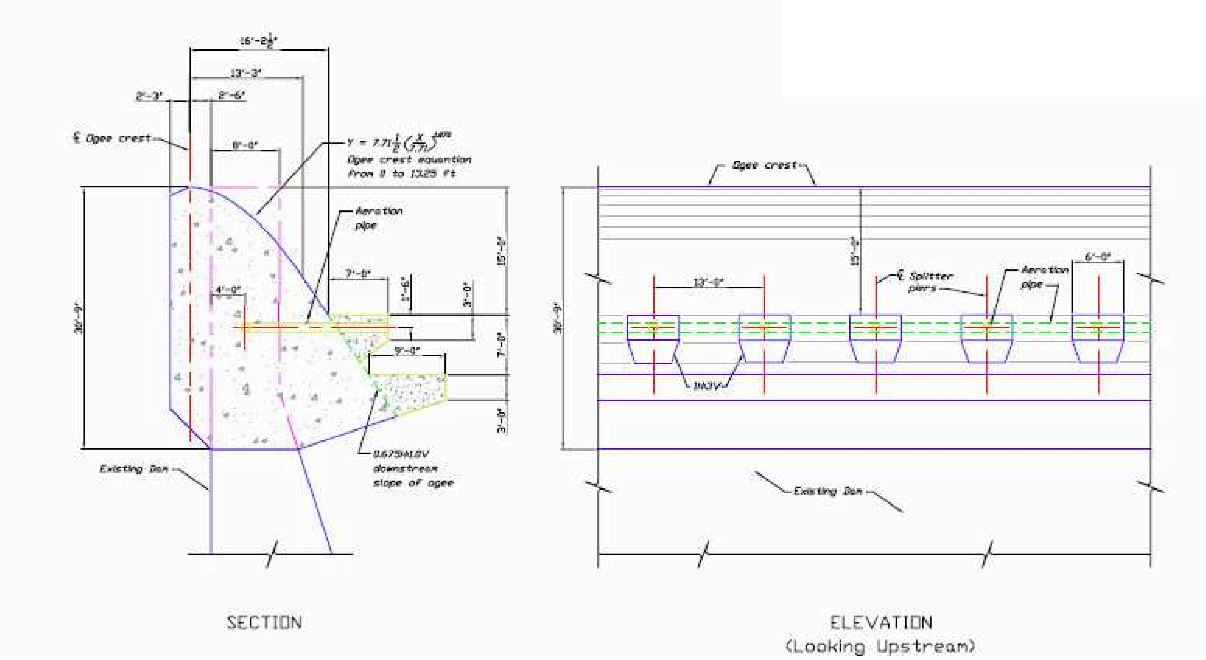

**Fig. 6** Roberts Crest design

The remaining flow passes in between adjacent splitters and impacts the lower lip, causing that flow to first spread laterally on the lip and then upwards. The "rooster tail" formed by the interacting flows on the lower lip underneath the upper row of splitters travels upwards through the flow coming over the upper splitters (**Fig. 7**). This results in significant break-up of the overtopping jet, thus reducing its erosive capacity on the rock below.

In concept the Falvey Crest is similar to the Roberts Crest. However, it utilizes curved splitters and a curved lower lip to increase the horizontal velocity of the jet (**Fig. 8**). A rooster tail also develops from the Falvey crest as flow off the upper splitter pier intersects flow off the lower lip. However, it is not as effective in breaking up the jet as the rooster tails produced by the Roberts Crest.

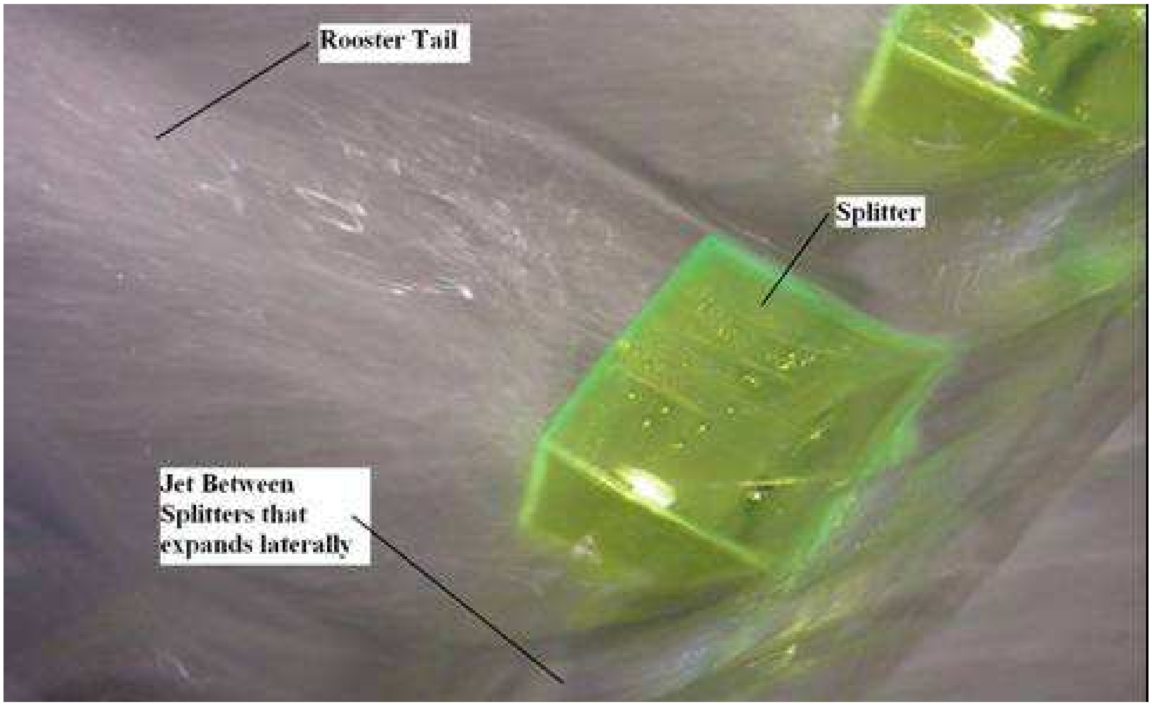

**Fig. 7** Formation of a "rooster tail".

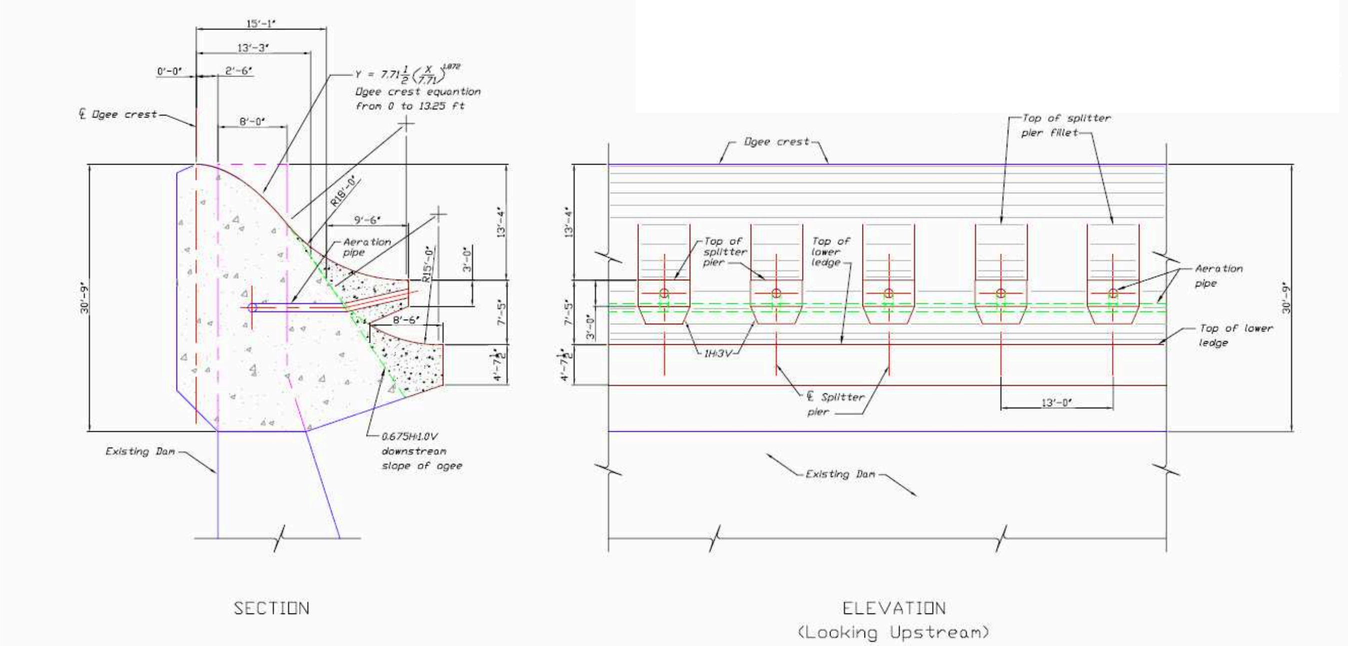

**Fig. 8** Falvey Crest design

**Fig. 9** shows both the Roberts and Falvey crests in action for the PMF. The high speed camera shots indicate that both crests induce significant jet turbulence, breaking it up into discreet water globules and droplets.

As indicated in **Table 2**, both crests were able to reduce pressures at the dam toe and at the abutments in comparison with the original crest, with the Roberts crest yielding the most reduction in erosive capacity. Both crests also increased the throw distance of the jet from the base of the dam (with the Falvey crest moving the jet footprint furthest away from the dam) accomplishing three things: 1) moving the scour hole location away from the dam toe, 2) eliminating the high velocity flows on the dam abutments, and 3) reducing the dynamic pressure on the rock downstream of the dam.

**Table 2** Change in Measured Dynamic Pressure Coefficients due to Crest Modification

| 100% PMF | | | | |
|---|---|---|---|---|
| Location | | Original | Modified Crests | |
| | | | Roberts | Falvey |
| Center | Cp | 0.212 | 0.030 | 0.082 |
| | C'p | 0.034 | 0.023 | 0.046 |
| Left Abutment | Cp | 0.618 | 0.554 | 0.426 |
| | C'p | 0.229 | 0.280 | 0.170 |
| Right Abutment | Cp | 0.301 | 0.052 | 0.208 |
| | C'p | 0.291 | 0.149 | 0.203 |

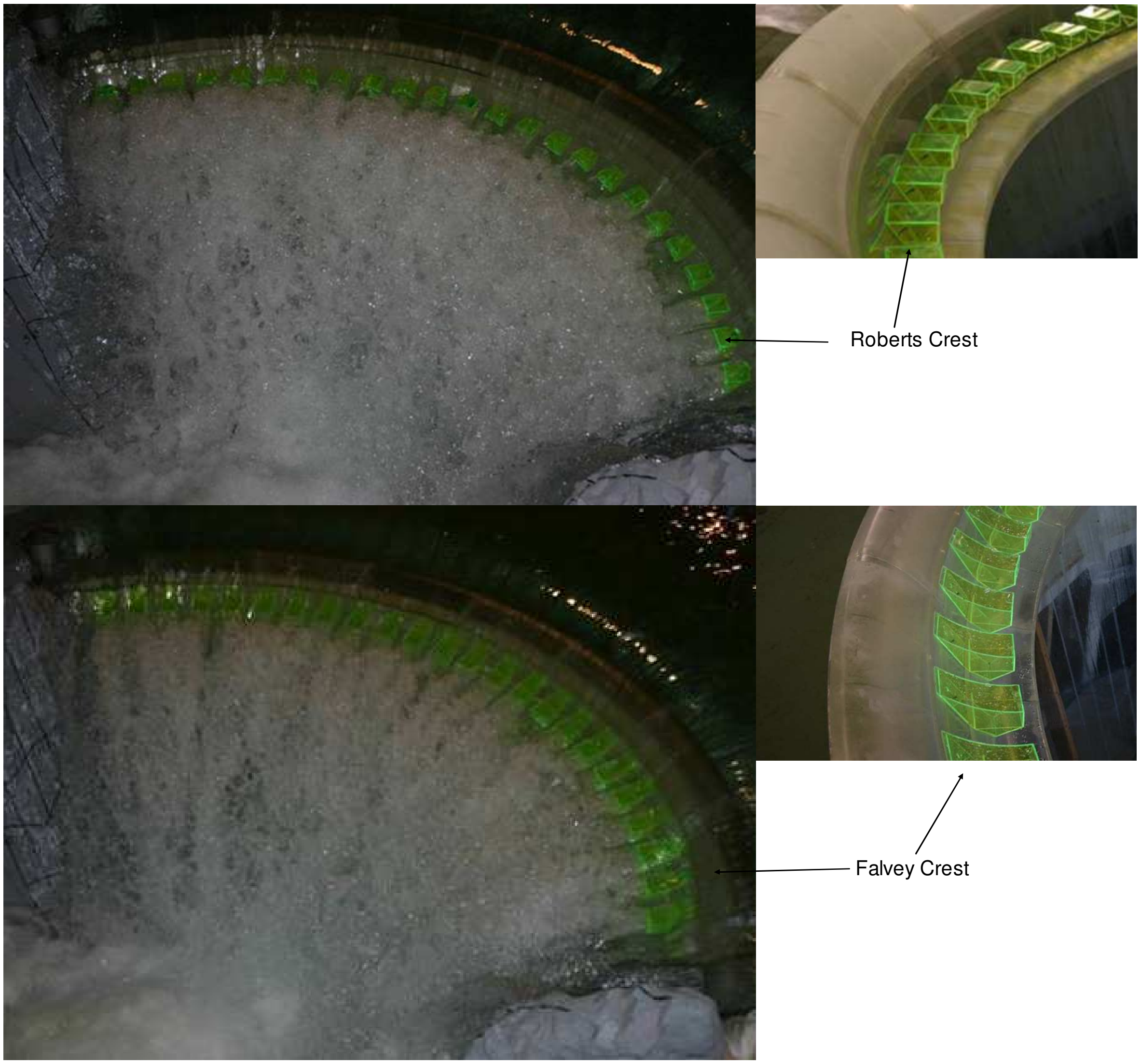

**Fig. 9** Roberts and Falvey Crests for 100% PMF.

## 5. CONCLUSIONS

Physical hydraulic models can be used as essential tools for increasing the reliability of theoretical scour predictions and identifying ideal crest modifications to safely reduce the erosive capacity of plunging jets overtopping dams. The following conclusions were made regarding this study:

- Measured pressure coefficients for the original crest configuration during the PMF flow showed relatively good agreement with the theoretical results obtained using the jet break-up length equation developed by Ervine et al. (1997) and the average and fluctuating dynamic pressure coefficient relationships developed by Castillo (2007), Bollaert (2002) and Ervine et al. (1997). This suggests the original estimates of scour depth, based on dynamic pressure estimates using these methods, are defensible.
- The presence of high-velocity flows shooting down the abutments for the original crest configuration could potentially increase the amount of scour at the dam toe beyond the theoretical estimates.
- The Roberts Crest was able to dissipate the greatest amount of energy. It produced a slightly shorter jet trajectory than the Falvey Crest. However, it still threw the jet significantly further than the original crest configuration.
- The Falvey Crest yielded a jet that impacted furthest away from toe of the dam. It was able to dissipate more energy than the original crest. However, it did not dissipate as much energy as the Roberts Crest.
- Given the results of the physical model study, the Roberts crest modification was recommended for the Eagle Nest Dam to pass flows associated with the PMF. The Roberts crest was selected because it gave the greatest amount of energy dissipation thus decreasing the erosive capacity of the jet, while still directing the overtopping jet away form the base of the dam. Additionally, the Roberts crest will likely prove easier to construct.
- The study indicates that the crest modifications significantly reduce the average dynamic pressure coefficient, but that the fluctuating dynamic pressure coefficient remains relatively unchanged. The only exception is the pressures measured at the left abutment. The reason for the almost insignificant decrease in average dynamic pressure at the left abutment is attributed to the topographical features at this location.
- The reduction in total pressure by implementing a crest modification such as the Roberts or Falvey Crest is anticipated to reduce scour of the dam foundation.

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