PENSTOCK SCOUR FORMATION AT BLUESTONE DAM

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ABSTRACT

This paper presents some results of a 3D scour assessment downstream of the penstocks of Bluestone Dam, West Virginia, US. The assessment makes use of the Comprehensive Scour Model (CSM) developed by Bollaert (2002, 2004). This practical engineering model is physics based and relates the hydrodynamic pressure fluctuations generated by flow spillage to the resistance of the downstream foundation to rock block ejection, rock mass fracturing and rock block peeling off. It has been developed based on detailed pressure measurements performed on a near-prototype scaled experimental facility and accounts for two-phase transient wave propagation of pressures inside joints of the rock. The model is not only able to predict the ultimate scour depth, but also the time and spatial evolution of the scour hole as a function of future flood events.

At Bluestone Dam, the jets issuing from the penstocks are very shallow and, as such, generate particular 3D flow turbulence conditions inside the flow dissipation area just downstream. The CSM has been adapted and applied to these shallow turbulent jets in order to allow a 3D spatial assessment of the time evolution of scour formation through the rocky foundation. This foundation mainly consists of ortho-quartzite, interbedded shale layers and claystone. These complex local geological conditions have been accounted for with depth in a quasi-3D manner. The model predicts future scour development by rock mass fracturing (CFM), rock block uplift (DI) and finally rock block peeling off by return currents (QSI, Bollaert 2009). The latter is of particular importance because it directly leads to regressive erosion towards the toe of the dam.

INTRODUCTION

Bluestone Dam was constructed in the 1940’s. The original design intent was to provide flood control for the Kanawha River Basin and hydroelectric power generation capacity. At the height of World War II, construction efforts were temporarily suspended because of labor and steel shortages. Once construction was re-initiated, the hydroelectric power function of the dam was revisited. It was decided at that time to only install the six, 19 - foot diameter penstocks and indefinitely delay the powerhouse and turbine construction. The original conservation pool was 1,490 feet assuming a hydroelectric function.

Because the dam currently serves as a flood control structure only, the operating pools are 1406 feet during winter months and 1,410 feet during summer months. The pool of record for the facility is elevation 1,506 feet, which occurred during a storm event in 1960.

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Phase I of the Bluestone DSA (Dam Safety Assurance) began in September 2000. Dam stability has been improved by the addition of mass concrete thrust blocks. This required the six penstocks to be extended. Additional discharge capacity during the PMF will be realized by the installation of sacrificial bulkheads on the downstream end of the penstocks.

Figure 1. General view of dam with 6 penstocks (left hand side) with thrust blocks and stop logs being installled. (courtesy: Public Affairs, USACE, Huntington District).

HYDROLOGIC DEFICIENCY

The original spillway design flood for Bluestone Dam produced an estimated 430,000 cfs of discharge through the outlet works and the stilling basin (no penstock flows). Current USACE criteria require that the design flood be based on the Probable Maximum Flood (PMF). This condition is expected to produce a maximum flow rate of about 880,000 cfs in the spillway area and an additional 165,000 cfs through the penstocks, for an upstream pool elevation of 1,546.8 ft. Hence, the overflow spillway, stilling basin and control structures were designed for less than half of the current design flood. Accordingly, this design flood is expected to generate severe damage to the structures and to scour the bedrock in the stilling basin and downstream of the penstocks.

Physical model studies conducted at ERDC (Vicksburg) support these concerns and showed high turbulence and scour potential near the spillway apron end sill and downstream of the penstocks.

Given the extreme character of the PMF event, under USACE guidelines, the primary objective is to retain the pool and stabilize the dam. In other words, extensive damage to energy dissipation systems and bedrock surface is expected and acceptable as long as the dam and the pool are maintained.

SCOUR MECHANISMS AT BLUESTONE DAM

The CSM estimates the ultimate depth of scour and the time evolution of scour in partially or totally fractured rock. The model is physically based and, at its origin, comprises a comprehensive assessment of three major physical processes that are responsible for rock mass destruction by turbulent flow impingement:

1) **CFM module**: hydrodynamic fracturing of closed-end rock joints (= joints that are not completely formed yet);
2) **DI module**: dynamic uplift of rock blocks (= once the joint network is completely formed).
3) **QSI module**: peeling off of protruding (flat-shaped) rock blocks generated by turbulent jets deviating on the rock mass and generating a high-velocity flow oriented towards upstream and parallel to protruding blocks.

The latter module computes the pressure fluctuations generated by the regressive wall jet and by the relative protrusion of distinct rock blocks/plates and determines whether blocks will be peeled off (ejected or detached from the matrix) or not. It defines regressive erosion towards the dam toe. The main parameters of influence are (Bollaert, 2009 and 2010):

- the angle and location of the impacting turbulent jet;
- the diffusion of this jet through the local water depth;
- the velocity of this jet upon deviation at the pool bottom into a wall jet;
- the percentage of the flow that is deviated towards upstream;
- the velocity profile of the wall jet towards upstream;
- the rock foundation or plunge pool bottom protrusion that may deviate the currents and generate dynamic pressure fluctuations.

Figure 2 illustrates how the low angle jet impacting the water-rock interface produces an upstream oriented wall jet that generates a backflow and turbulent flow conditions at protruding rock blocks. This backflow is transformed by the numerical model into turbulent uplift pressures that may detach (peel off) rock blocks. The model automatically adapts the strength of the backflow and related turbulent pressure fluctuations at each point of the numerical grid to the evolution of the scour hole shape. Scour by peeling off ends when the uplift pressures are not able anymore to detach and/or uplift distinct rock blocks/plates.

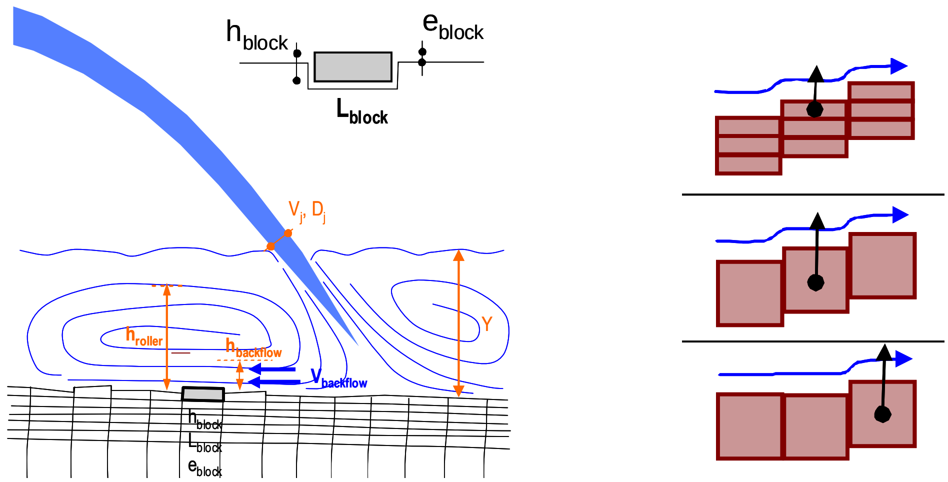


Figure 2. Peeling off of rock blocks under shallow jet impact (Bollaert, 2009)

The different scour mechanisms that may happen downstream of the penstocks are determined in Table 1 and qualitatively illustrated at Figure 3:

Table 1. Scour mechanisms studied at Bluestone Dam

Mechanism	Symbol	Functioning	Validity	Output
Comprehensive **F**racture **M**echanics	CFM	progressive break-up of existing rock joints due to jet impact	area of turbulent jet impingement	Time evolution of scour development
Dynamic **I**mpulsion	DI	sudden vertical ejection of rock blocks generated by pressure differences over and under the block	area of turbulent jet impingement	Ultimate scour depth
Quasi-**S**teady **I**mpulsion	QSI	peeling off of protruding rock plates due to wall jet generated by turbulent impingement	area between dam and location of turbulent jet impingement	Ultimate scour depth

Each of these mechanisms allows quantifying the ultimate scour depth related to the considered flow event. The CFM method also allows quantifying the time evolution of scour development. The other mechanisms do not allow expressing such a time evolution.

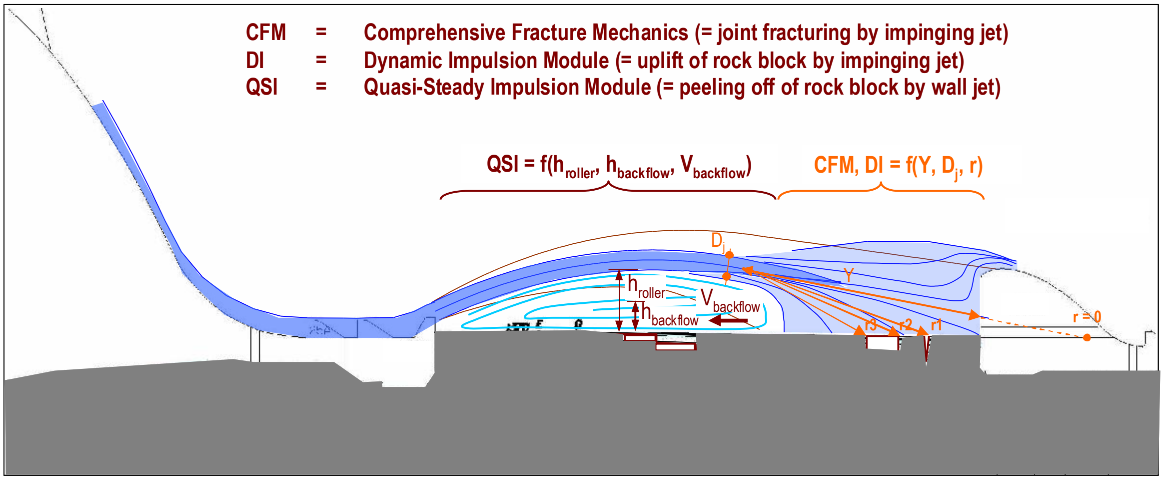


Figure 3. Main scour mechanisms at Bluestone Dam (at stilling basin).

PENSTOCK OPERATING CONDITIONS

The following penstock operating conditions have been computed:

Location [-]	Spillway condition N°	6 Penstocks discharge [cfs]	Crest+sluice gates discharge [cfs]	Pool elevation [NGVD]	TW elevation [NGVD]
Penstock area	3	80,000	-	1,480.0	1,379.0
Penstock area	4	125,000	-	1,505.0	1,384.0
Penstock area	8	145,000	-	1,530.0	1,402.0
Penstock area	11	151,000	-	1,546.8	1,409.5

The penstocks discharge mentioned is for all 6 penstocks operating. Spillway condition N°11 represents the new PMF estimate. Also, condition N°8 represents an intermediate discharge between the old PMF estimate and condition 11. Conditions 3 and 4 are lower spillway discharges that allow evaluating the impact of lower velocity jets issuing from the penstock outlets on the downstream rock bed.

Shallow jet flow conditions

The flow conditions in the penstock area are governed by the following aspects:

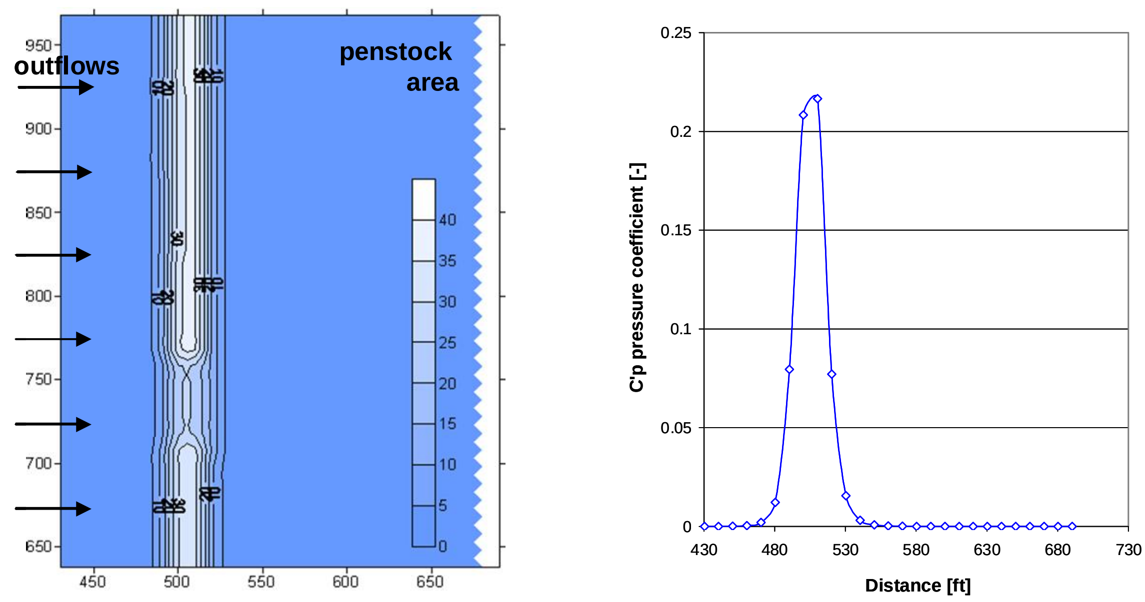
1. *Shallow jet flow through the penstock conduits*: Numerical computations have been performed of the flow conditions at the outlet section of the penstock conduits. These computations determine the issuing jet height and velocity by neglecting the head losses through the penstock conduits.
2. *Turbulent shallow jet diffusion through the water depth in the penstock area*: Numerical computations have been performed of the diffusion of the turbulent jet.

The penstock outlet flows have been systematically considered non-submerged by the downstream tailwater level (most conservative assumption).

The diffusion of the penstock jets happens under a low angle with the horizontal. For such conditions, scour formation occurs more downstream of the dam face. The location of deepest scour directly depends on the jet issuance angle and velocity at the penstock outlets. As such, as shown by the scour results, relatively low discharges may provide deep scour close to the dam toe and may be more dangerous with respect to dam stability.

Shallow jet dynamic pressure fluctuations

The mean and fluctuating (RMS) dynamic pressures generated by the jet diffusing through the penstock water depth have been defined. Figure 4 shows an example of the fluctuating (RMS) dynamic pressures for 151,000 cfs through the 6 penstocks (PMF). Figure 4a shows the pressure values ([ft]) over the penstock area, while Figure 4b shows a cross-sectional view of the non-dimensional pressure fluctuation coefficient C'_p.



a) Dynamic pressure fluctuations [ft]; b) Pressure fluctuation coefficient C’p [-]

Figure 4. Fluctuating dynamic pressure distribution over the penstock area (flows from the left to the right): a) pressure values [ft]; b) pressure coefficient C’p ([-])

GEOMECHANICAL CHARACTERISTICS

Site geology

The dam site is located near the axis of the Bellepoint syncline, and the rock strata have very gentle dips into the dam site both from the northwest and the southeast (FMSM, 2003). The Stony Gap Sandstone (including orthoquartzite, siltstone and claystone) is variably interbedded with carbonaceous shale, has a thickness of about 60 feet, and forms the bed of the New River at the dam site. Underlying the Stony Gap Sandstone is the Coney Shale. The rocks lying above the Stony Gap Sandstone form the sides of the valley and are primarily shale. The beds are lenticular in nature and vary substantially, both vertically and horizontally. Specifically in the area of foundation work discussed herein, local anticlinal folding was found near Monolith 15, along with non-horizontal bedding surfaces and a significant fault and related fracture zone.

Dominant lithologies

The dominant rock lithologies that are found at the dam site are described as follows (FMSM, 2003):

- Orthoquartzite (OQ): light gray, very hard and very fine grained, with occasional thin, black carbonaceous shale stringers. Contains numerous discontinuities.
- Interbedded orthoquartzite and shale (IB): light gray, very hard, very fine grained orthoquartzite with undulating layers of moderately hard, black, carbonaceous shale, thinly bedded.
- Claystone (CL): present as distinct layers in the Stony Gap sandstone, at significant depths.

Jointing and discontinuities

The bedrock is only slightly disturbed by folding and contains numerous vertical and quasi-horizontal joints. A general view of the penstock outcrop area is given in Figure 5 (Courtesy: Public Affairs, USACE, Huntington).

The main structure of the bedrock with depth was made available by means of a detailed geologic section for each monolith. This section has been directly used as input to the numerical scour model. For each monolith, two vertical cuts into the geologic section have been made, one through the middle of the penstock area, and another one in the vicinity of the end of the penstock area.

Furthermore, the numerous joints present at the dam site have been extensively studied. First of all, a detailed analysis of the 2008 rock outcrop data allowed determining the strikes and dips of the main joint sets in the vicinity of the penstock area. As can be seen in Figure 6, at both left and right hand sides of the penstock area (looking downstream), two quasi-vertical dipping joint sets can be distinguished. These strike more or less West-East, making an angle of about 45° with the dam axis. One joint set strikes almost North-South, i.e. perpendicular to the aforementioned joint sets.

Furthermore, two main perpendicular joint set orientations can be distinguished at the dam site: these are oriented almost east-west and north-south, similar to the previously found orientations based on the 2008 outcrop data.

Figure 5. Photo showing the penstock area in detail, before installing the thrust blocks. (courtesy: Public Affairs, USACE, Huntington District).

Joint spacing

The spacing of the joints highly depends on strike and dip. Detailed analysis of borehole data showed that the joint set that strikes almost east-west has a rather small average spacing of about 1.5-3.5 ft, while the joint set that strikes almost north-south has a much higher average spacing of about 5 to 16 ft. In orthoquartzite, the average vertical spacing is between 0.30 and 1.5 ft, while in interbedded OQ-shale, the average vertical spacing is only 0.15 to 0.30 ft.

Dip trends

The quasi-horizontal joint sets have generally quite low dips between -5 and +5°. Depending on the location, these dips can be either towards the dam or away from the dam.

Rock block shape

Based on the different joint set spacings and orientations, as well as on site observations, the rock block shape at the dam site is typically that of a thick plate, with the block side lengths being a multiple of the block height (4-5 times).

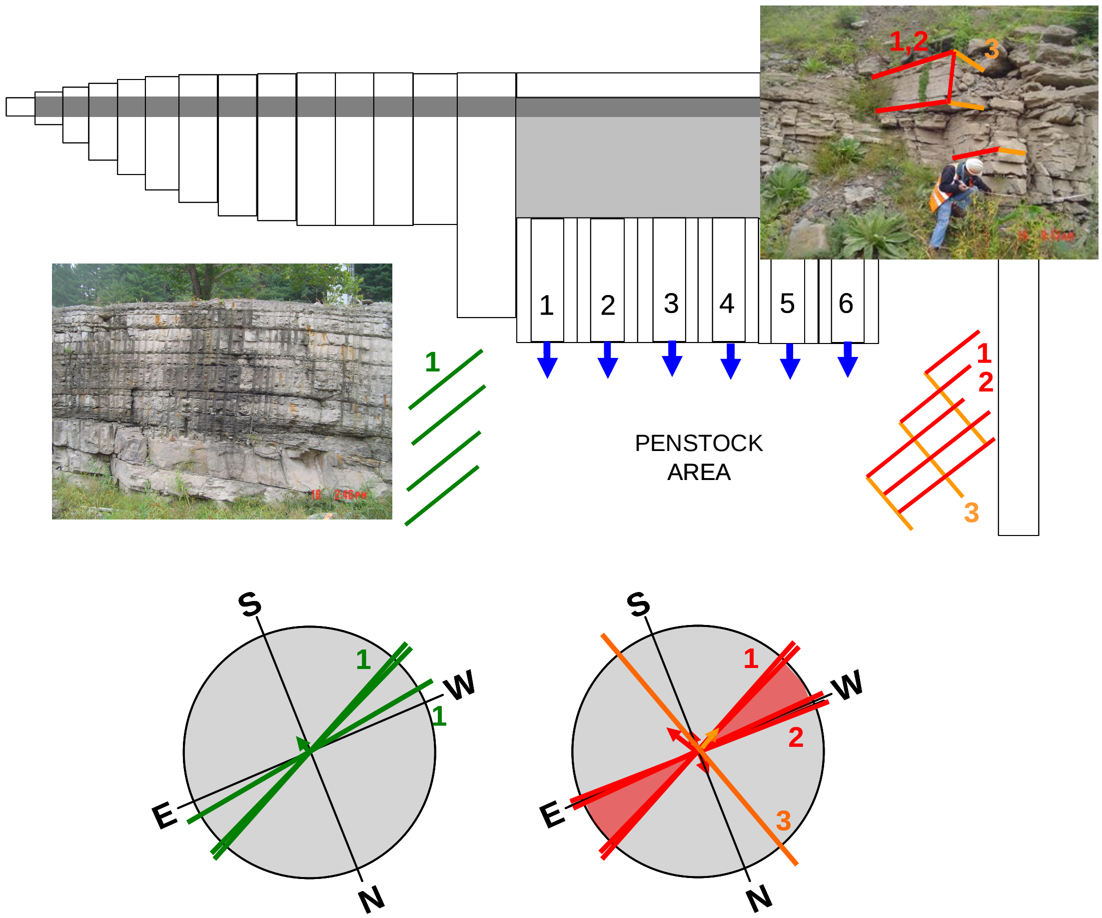


Figure 6. Main joint sets in the penstock area, based on the 2008 rock outcrop data.

SCOUR COMPUTATIONS

Program of scour computations

Scour computations have been performed in the following manner (Bollaert, 2009):

- 4 scour evaluation methods (CFM, DI, QSI, Erodibility Index = EIM)
- 6 penstock monoliths (M16-M21)
- 3 parametric assumptions on rock mass quality
- 26 grid points per penstock monolith
- 4 dam operating conditions
- 21 time dependant computations for CFM method
- 1 geological profile per monolith

The model verification needed 418 scour computations (all methods together, spillway and penstock monoliths), and an additional 2,160 time-dependent computations for the CFM method. The scour analysis needed 28,500 scour computations (all methods together) and an additional 142,500 time-dependent computations for the CFM method.

Numerical grid

The numerical grid used for the computations is presented in Figure 7. A local coordinate system has been used. The penstock area extends from the outlet section of the penstock conduits to the current road across the penstock area downstream. Whenever scour occurs further downstream, the grid has been extended. The Y-coordinate extends from monolith M16 to monolith M21. The grid size is equal in both X- and Y directions. Along the Y-direction, however, only one longitudinal line of grid points is computed per monolith. This is sufficient because of the lateral homogeneity of both the hydraulics and the geologic sections across each monolith.

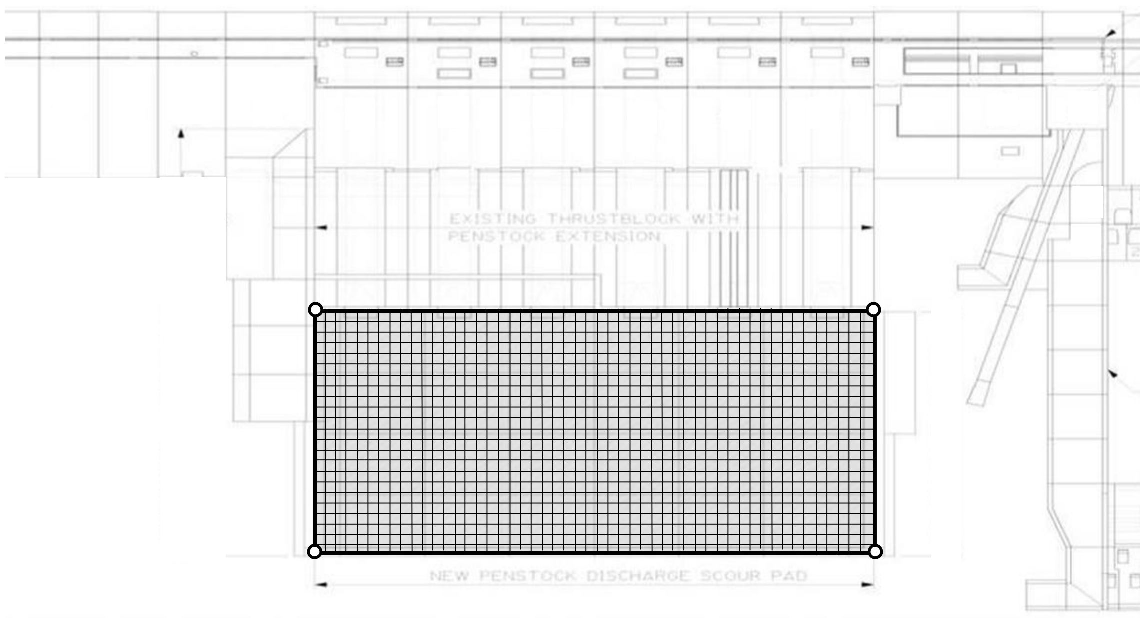


Figure 7. Numerical grid used for the penstock scour computations (Bollaert, 2009)

Parametric assumptions

Besides the different scour evaluation methods (CFM, DI, QSI and EIM), three main parametric assumptions have been made for the computations. These assumptions relate to the vulnerability of the rock mass layers to scour and are briefly outlined below:

Conservative parametric assumptions

Conservative (= lowest degree of safety margin) estimate of the rock mass resistance to scour, i.e. lower bound of UCS values, very low rock block heights, high degree of initial fracturing, lower bound of rock density, etc.

Average parametric assumptions

Average (= most reasonable) estimate of the rock mass resistance to scour, i.e. medium bound of UCS values, medium rock block heights, medium degree of initial fracturing, medium bound of rock density, etc.

Beneficial parametric assumptions

Beneficial (= optimistic but still plausible) estimate of the rock mass resistance to scour, i.e. higher bound of UCS values, highest possible rock block heights, lowest possible degree of initial fracturing, upper bound of rock density, etc.

Results of scour computations

For all dam operating conditions, the jets issuing from the penstock outlet sections are considered to be unsubmerged by the downstream tailwater. The latter has been taken equal to the local rock bed, despite the locally higher tailwater levels downstream of the penstock area. This corresponds to realistic assumptions for scour estimates.

Figure 8 shows qualitatively the results of penstock scour computations for the new PMF condition (i.e. condition 11, with water levels corresponding to a discharge of 880,000 cfs over the spillway) at one of the monoliths computed. The discharge through the penstocks is defined at 25,100 cfs per penstock, or about 151,000 cfs in total.

The following qualitative conclusions may be drawn regarding scour at the penstocks:

1. All overburden or added material will be immediately scoured out at the start of the event.
2. The rock mass in the vicinity of the penstock outlets will scour, until a reasonable depth which depends on the parametric assumptions made.
3. Further downstream, scour may become more significant. The deepest scour elevation will depend on the initial degree of break-up of the rock mass as a function of depth.
4. Regardless of the scour forming towards downstream and the parametric assumptions, this deep scour hole is not expected to move towards upstream and undercut the dam.

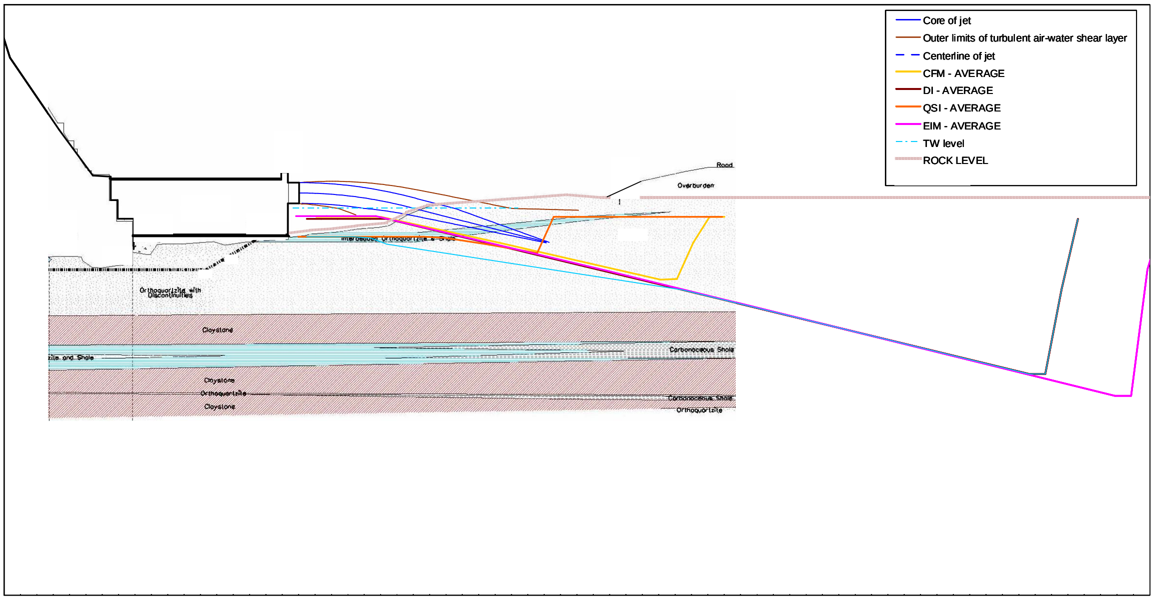


Figure 8. Qualitative scour potential in the penstock area for average parametric assumptions and for a total discharge of 151,000 cfs.

The summarizing results for monoliths M16 to M21 are presented below for condition 3, i.e. with water levels corresponding to 87,000 cfs over the spillway. The upstream reservoir level is at 1,480 ft.

Figure 9 presents qualitatively the scour potential in the penstock area for <u>average</u> parametric assumptions, for a discharge through the penstocks of 13,500 cfs per penstock, or about 80,000 cfs in total.

Compared to the previously computed operating conditions, the present jet shows almost no scour in the vicinity of the penstock outlet sections. This is due to the significant decrease of the jet velocity issuing from the penstocks, even with a shorter fall distance and a higher angle of impact of the jet upon the rock mass.

Also, the scour potential based on fracturing of the rock mass (CFM method) is much less than for the 151,000 cfs operating condition. In other words, if the rock were considered as having a certain resistance to hydrofracturing (and thus not fully broken up), only limited scour would occur in the penstock area. Only loose material at the rock surface would probably be scoured out.

Nevertheless, when considering the rock mass as fully broken up with depth, ultimate scour depth may become even slightly higher than for the previous operating condition, generated by the higher angle of impact of the jet upon the rock mass and thus a higher angle of scour progression with depth in the rock mass.

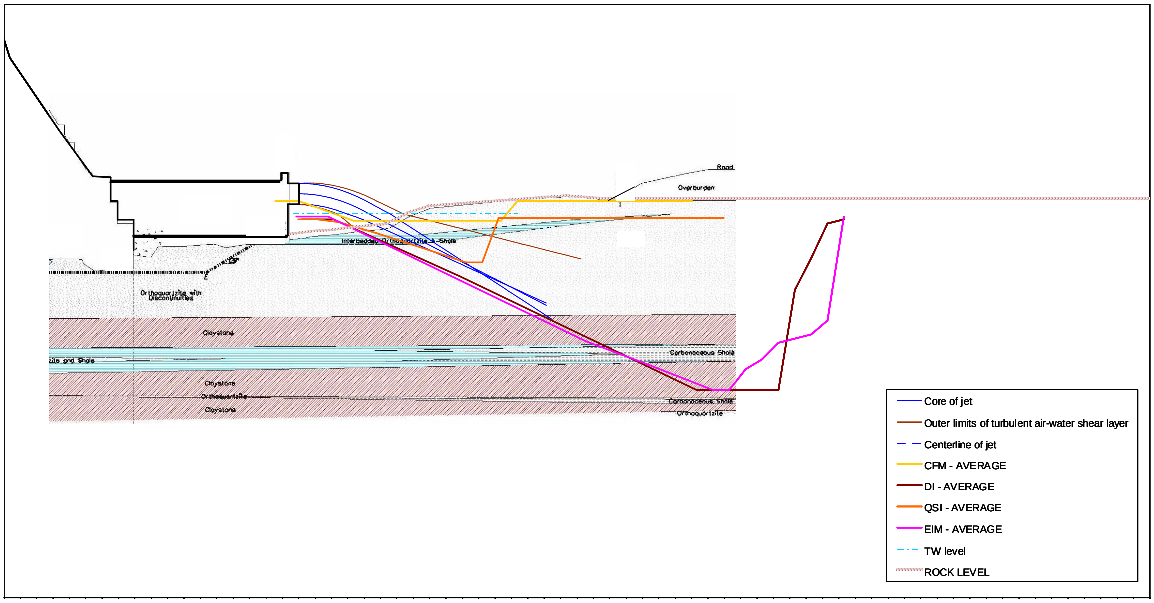


Figure 9. Qualitative scour potential in the penstock area for average parametric assumptions and for a total discharge of 80,000 cfs.

In general, potential scour in the penstock area will occur quickly during any kind of flood event, regardless of the upstream reservoir level. This is due to the initial high degree of break-up of the rock mass layers, which means that the phase of hydro-fracturing of the rock is currently almost completed and that the rock can be represented by distinct layers of rock blocks. Furthermore, the rock blocks have a plate-like shape, which means they are particularly vulnerable to ejection or peeling off.

When considering the rock as completely fractured (QSI and DI scour evaluation methods), the global scour potential in the penstock area is quite independent of the penstock operating conditions, i.e. the shape and the ultimate extent of scour are quite similar for all operating conditions computed. Within the immediate vicinity of the penstock outlet sections, scour potential is not constant but depends on both the location of jet impact and the velocity of the jet upon impact.

As such, the worst toe scour was surprisingly observed for the 125,000 cfs flow condition, combining a relatively high jet velocity with a quite short fall distance of the jet. For the highest flow conditions tested, jet velocities were higher but the jet impacted much further downstream. For the lowest flow conditions tested, the jets impacted somewhat closer to the penstock outlets, but the corresponding jet velocities were significantly lower.

When assuming that the rock still has to be fractured before being ejected or peeled off by the turbulent flow, the situation is different. Only the highest flow conditions (151,000 cfs) are able to hydrofracture the rock mass and generate scour.

CONCLUSIONS

The Comprehensive Scour Model (CSM) has been applied to estimate scour potential at the penstocks of Bluestone Dam, West Virginia, US. As the turbulent jets issuing from the penstocks impact the downstream bedrock under a very low angle, numerical implementation of the main break-up mechanisms responsible for scour, i.e. uplift, fracturing and peeling off of rock blocks, has been adapted to this particular situation.

Especially the Quasi-Steady Impulsion module (QSI) has shown to be relevant and efficient in predicting potential scour regression from the point of jet impact back towards the toe of the penstock thrust blocks. This module computes progressive "peeling off" of distinct rock blocks and plates and is particularly relevant in case of stratified bedrock.

The computations account for the local lithology with depth and provide a 3D detailed comprehension of potential scour in the area downstream of the penstock thrust blocks.

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