Wall jet rock scour in plunge pools: a quasi-3D prediction model

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This paper presents a new computational method for prediction of rock scour in plunge pools and stilling basins of high-head dams. The method accounts for 2D vertical diffusion and subsequent deflection of high-velocity jets at the bedrock. This forms wall jets that are being deviated by protruding rock blocks. The model computes the corresponding turbulent pressures that may eject single blocks. It is applicable along the bedrock situated outside of the area of jet impingement, both towards the dam and towards downstream. As such, it is complementary to the existing rock scour prediction methods being implemented in the Comprehensive Scour Model (CSM, Bollaert 2004), which are based on fracturing and transient ejection of rock blocks situated inside the turbulent shear layer of the impinging jet. By simultaneous application of these methods to a series of 2D vertical jet slices, a quasi-3D rock scour prediction model is obtained. The new model allows prediction of regressive scour towards the dam toe. Real-life case studies for both shallow and plunging jets illustrate the major outcomes of the presented approach, allowing reliable prediction of future scour evolution.

P lunge pool rock scour downstream of highhead dams is governed by the hydrodynamic action at the water-rock interface. Despite the quasi-2D diffusion of water jets through the plunge pool depth, the presence of this interface strongly deflects the jets from their point of impingement towards upstream and downstream. The related high-velocity wall jets strongly interact with the pool bottom before boiling up at the water surface or being transferred towards the downstream river course.

As such, scour formation along these areas of the pool bottom is governed by physics that are somewhat different from the processes responsible for scour in the turbulent shear layer of a diffusing jet impinging on the pool bottom. While the latter scour is associated with dynamic pressure fluctuations generated by the turbulent eddies of the developed jet, the former scour is more related to the presence of quasi-steady high-velocity flows parallel to the bottom and being suddenly deviated by protruding rock blocks, generating so quasi-steady uplift forces on rock blocks.

Physics based time-dependant rock scour inside the turbulent shear layer of the jet, i.e. in the jet impingement area at the pool bottom, has been assessed by the Comprehensive Scour Model (CSM) as described by Bollaert (2004). Its companion part outside of this turbulent shear layer, i.e. along the pool bottom outside of the jet impingement area - also called the wall jet area - is described and developed in the present paper.

Hence, combining both these areas and accounting for local geomechanic parameters allows to cover timedependant rock scour potential along the entire pool bottom in a 2D manner. Also, systematically performing such an analysis along subsequently aligned 2D jet diffusion and deflection profiles makes the process quasi-3D.

The present paper explains the methodology and basic equations for rock scour assessment along the pool bottom outside of the jet impingement area and outlines how this scour formation is related to scour at the point of jet impingement itself. The result is a new engineering model for quasi-3D time-dependant scour prediction that allows assessment of regressive scour towards the dam and of the shape of the scour hole from the dam towards the downstream river course. The new model has been successfully calibrated and applied to two real cases of 3D rock scour: Bluestone Dam, West Virginia, United States, with very shallow jets impacting the unlined downstream stilling basin (Bollaert, 2011); and Kariba Dam in Zambia-Zimbabwe, with almost vertically plunging jets eroding the downstream rockbed since 1962 (Bollaert, 2005).

1. Jet diffusion and deflection

The diffusion and bottom deflection of a high-velocity jet through a water pool has been extensively described by a large number of researchers, amongst which Beltaos and Rajaratnam (1973). As illustrated in Figure 2, they differentiated three main regions of interest: the free jet region, the jet impingement region and the wall jet region. These regions are of particular interest to plunge pool rock scour and are described in detail hereafter.



Figure 1: Summary of axial jet velocity decay with increasing ratio of pool depth Z to jet diameter at impact D_{j} .



Figure 2: Plane jet deflection on a flat bottom according to Reich (1927) and wall jet velocity profiles following Beltaos & Rajaratnam, (1973).

1.1. Jet diffusion through pool depth

Jet diffusion through the plunge pool water depth starts in the free jet region, where self-preserving velocity and pressure profiles are valid. The jet in this area is not influenced by the presence of the pool bottom. Several researchers have studied the velocity and pressure distributions in this area, see Figure 1 (Hartung & Hausler (1973), Bohrer et al. (1998)). Most studies relate the axial jet velocity decay to the local jet thickness or diameter or to the inverse of the water depth Z. Bohrer et al. (1998) studied the velocity decay for both compact and broken-up jets. Following Hartung & Hausler (1973), the relationship for V(Z) as a function of the jet velocity at impact in the pool V_i is written:

$$\frac{V(Z)}{V_i} = \frac{Zcore}{Z} \quad \text{for circular jets} \quad [1]$$
$$\frac{V(Z)}{V_i} = \sqrt{\frac{Zcore}{Z}} \quad \text{for rectangular jets} \quad [2]$$

in which Z_{core} stands for the distance necessary for the jet to diffuse its core through the pool depth. This distance is generally taken at 4-5 times the jet diameter at impact D_{j} .

The jet impingement region generates stagnation pressures due to deflection of the turbulent shear layer of the jet at the bottom. While most researchers mainly focused on the time-averaged pressure and velocity values, Ervine et al. (1997) and Bollaert & Schleiss (2005) also assessed the turbulent pressure fluctuations in this same area. As such, the stagnation pressures are described by a set of dynamic pressure coefficients that are used as input to the fracture mechanics and block uplift modules of the Comprehensive Scour Model (Bollaert, 2004). The average flow velocity at the point of jet deflection V_{Zbottom} is used as initial velocity to define the wall jet region (see Figure 2).

1.2. Wall jet parallel to pool bottom

The wall jet region describes the region of flow parallel to the bottom, outside of the impingement region. This region is generally characterised by self-similarity of flow velocity profiles.

Nevertheless, in case of protruding rock blocks along the bottom, the flow may be deflected by these blocks, which generates severe turbulent pressure fluctuations. In contrast with turbulent wall pressures that are generated by turbulent eddies of the flow itself, these pressure fluctuations are of quasi-steady character (Hofland, 2005; Bollaert & Hofland 2004). As such, they may be able to generate significant lift and drag forces on the protruding rock blocks. Bollaert & Hofland (2004) were able to measure the quasi-steady flow velocity field and related pressure forces on blocks in a small-scale laboratory model at TU Delft. They concluded that rock blocks may be easily uplifted.

The deflection of the jet at the pool bottom occurs in both the up-and downstream directions. The importance of each of these deflections directly depends on the angle δ of the jet upon impact in the pool. As shown in Figure 2, based on Reich (1927), a theoretical approach for plane jets with initial discharge q_{total} and thickness D_j impinging on a flat plate relates the respective discharges q_{up} and q_{down} and thicknesses h_{up} and h_{down} by means of the cosinus of the jet angle with the horizontal δ :

$$\frac{q_{up}}{q_{total}} = \frac{h_{up}}{D_j} = \frac{1}{2} \cdot \left(1 - \cos\delta\right) \qquad [3]$$

$$\frac{q_{down}}{q_{total}} = \frac{h_{down}}{D_j} = \frac{1}{2} \cdot \left(1 + \cos\delta\right) \quad [4]$$

The table hereunder shows the up-and downstream deviated parts of the total flow for different jet angles δ .

Jet angle δ	10 °	20 °	30 °	40 °	90°	
\mathbf{q}_{up}	1.5%	6%	7%	12%	50%	
q _{down}	98.5%	94%	93%	88%	50%	

Once the jet deflected, the generated wall jets may be characterized by their initial flow velocity $V_{Zbottom}$ and their initial thickness $h_{up/down}$ at the point of deflection. Initiating from this singular location, the wall jets develop radially outwards following self-preserving velocity profiles (Beltaos & Rajaratnam, 1973) as given by the following equation:

$$\frac{V_{X,\max}}{V_{Zbottom}} = \frac{3.5}{\sqrt{X/h_{down}}}$$
[5]

 $V_{Zbottom}$ depends on the diffusion angle of the impinging jet and on its development length through the water depth Z, based on equations [1] and [2]. $V_{Zbottom}$ continuously changes during scour formation. $V_{X,max}$

expresses the decay of the maximum cross-sectional jet velocity with the relative distance from the start of the wall jet (lateral distance X divided by the initial thickness of the deflected jet $h_{up/down}$). It can be observed that, with increasing distance from the jet deflection point, the jet velocity profile flattens and the jet thickness increases.

1.2. Quasi-steady pressures at protruding blocks

This decreasing velocity is of direct relevance to the potential generation of quasi-steady stagnation pressures at rock blocks protruding along the pool bottom. Several researchers have defined this pressure by means of an uplift pressure coefficient C_{uplift} expressing the pressure as a percentage of the kinetic energy $V_{z,m}^2/2g$ of the quasi-parallel flow deviated by the block.

Reinius (1986) extensively studied potential net uplift stagnation pressures for different configurations of block protrusion and joint angles subjected to a high-velocity flow parallel to the pool bottom. The results are summarized at Figure 3. By subtracting the surface pressure coefficient C_{surf} from the joint pressure coefficient C_{joint} , net uplift pressure coefficients C_{uplift} of up to 0.67 have been measured. For practice, sound values are situated between 0.10 and 0.50, depending on the importance of the protrusion of the block and on the joint angle. For joint angles that are oriented against the flow together with negative steps, negative or stabilizing coefficients are obtained.

	h _{block} /e _{block}	β_{block}	C _{surf}	C _{joint}	C _{uplift}	Comment	
	17-29	0°	0.030	0.250	0.220		D.
	17-29	0°	0.030	0.250	0.220		
	17-29	0°	0.020	0.105	0.085		Turbulent Shearlayer Huctualing Futur
Cupw Cdown	17-34	0°	-0.010	0.145	0.155		V _{x,m} C _{sut}
	4-9	0°	0.075	-0.110	-0.070	block stabilizing forces	Cjoint
	4-10	3°	0.030	0.350	0.310		β _{block}
	2-4	9°	-0.10-0.17	0.36-0.55	0.37-0.47		
	1.0-2.5	18°	-0.15-0.00	0.23-0.40	0.25-0.45		Quasi-steady lift force F _{QSL}
	4.2-8.7	-3°	0.02-0.13	-0.105	-0.070	block stabilizing forces	$F_{QSL} = (C_{joint} - C_{surf}) \cdot L_{block} \cdot \frac{V_{x,m}^2}{2g}$ $V_{x,m} = f(X, h_{down}, V_{Zbottom})$
TE	1.0-2.3	-18°	-0.10-0.16	-0.075	-0.150	block stabilizing forces	$h_{down} = D_j \cdot \frac{q_{down}}{q_{total}}$

Figure 3: Summary of quasi-steady pressures over and under protruding rock blocks subjected to parallel high-velocity flow following Reinius (1986).

2. Quasi-Steady Impulsion model

The Quasi-Steady Impulsion Model (hereafter: QSI) makes use of the aforementioned physics to mathematically express the potential for rock scour along the zones of the pool bottom that are situated both upand downstream of the point of jet impingement, i.e. where wall jets form.

As such, the model allows estimating the shape of the scouring pool bottom towards downstream, as well as the risk and the intensity of potential regressive scour towards the dam toe. The latter phenomenon often is of particular importance to dam stability.

2.1. Step-by-step methodology

The step-by-step methodology used by the QSI model is visualized in Figure 5 and may be described by a sequential application of a series of 6 sub-models. These sub-models are presented more in detail hereafter.

The QSI model computations are performed following distinct computational lines, each line containing grid points as shown in Figure 4. The sub-vertical computational lines are located at fixed horizontal distances (X1, X2, etc.) from the jet impingement point and oriented following the main angle of impact of the jet at the water-rock interface (δ). This horizontal distance Dx defines the degree of precision of the computed scour hole shape and is typically between 1 and 10 meters. The sub-vertical distance Dz between 2 adjacent grid points may depend on the layering character of the bedrock. Typical values for the computations are between 0.25 m and 1 m. It has to be noted that the distances between the grid points and the computational lines do not necessarily have to be related to real rock block sizes.

Scour computations are then performed along a vertical 2D-plane (jet slice) and on a line-by-line basis, each line providing its ultimate scour depth independently from the other lines. Also, scour development is considered oriented following the main angle of impact of the jet δ .

By repeating the computations for different vertical 2D planes (jet slices), a quasi-3D scour hole shape is being obtained for a given flood event.



Figure 4: Sub-vertical lines of computation of QSI model

2.2. Sub-models

In the following, the different sub-models that are applied sequentially are discussed with more detail.

2.1.1 SUB-MODEL 1: FREE FALLING JET

The free falling jet sub-model defines the jet location (X), velocity $(V_{z,j})$, shape and diameter (D_j) upon impact in the pool. These parameters are defined as a function of the jet velocity $(V_{z,i})$ and jet diameter (D_i) at issuance from the dam, modified by gravitational acceleration during the fall of the jet. More details can be found in Bollaert (2004).

2.1.2 SUB-MODEL 2: 2D JET DIFFUSION

Based upon the jet characteristics upon impact in the pool, the evolution with depth of the axial velocity of the jet diffusing through the pool ($V_{Zbottom}$) may be computed based on the following methods:

- Jet diffusion angle and conservation of mass. (typical angles are between 6 and 14°)
- Laboratory measurements performed by Bohrer et al. (1998) for compact jets
- Laboratory measurements performed by Hartung & Hausler (1973)

Figure 1 compares jet velocities for a given pool and a jet angle with the horizontal of 60°. Up to a water depth of about 4-5 times the jet diameter (or jet thickness) at impact in the pool, the axial jet velocity remains constant (core of the jet). For deeper pools, jet diffusion progressively decreases the axial jet velocity.

The measurements performed by Hartung & Hausler (1973) for circular jets are in good agreement with the assumption of a constant 14° jet diffusion angle for a fully developed jet. On the contrary, the values based on Bohrer et al. (1998) seem significantly lower for pool depth to jet diameter ratios of up to about 20.

2.1.3 SUB-MODEL 3: 2D JET DEFLECTION

Based upon the pool depth and the angle and location of impact of the jet on the pool surface, the impact point of the jet near the bedrock may be defined. The angle of the jet through the pool depth (δ) may be roughly taken as the angle of the jet at impact on the pool surface. Although this is somehow a simplification of reality, this impact point is used as the starting point for the development of wall jets radially outwards, both towards up-and downstream.

Next, the parts of the total flow rate (q_{total}) deviated towards up-and downstream are defined as percentages of the total rate, based on equations [3] and [4].

2.1.4 SUB-MODELS 4a/4b: WALL JET

The flow separation as computed in § 2.1.3 defines the initial heights of the wall jets towards up-and downstream. These are simply defined as the flow percentages applied to the jet diameter or thickness upon pool impact. Even if reality is much more complex, this approach has the merit to respect the discharge distribution between both wall jets in a simple manner.

These initial jet thicknesses represent the length scale h_{down} in equation [5], and thus also the degree of decrease of the max. wall jet velocity with increasing distance X from the starting point.

Then, again based on equation [5], the wall jet velocity $V_{X,max}$ may be defined as a function of the radial distance X away from the jet's stagnation point. To simplify the approach, it is assumed that this max. wall jet velocity applies at the bottom and is directly responsible for the generation of quasi-steady pressure gradients on protruding rock blocks.

2.1.5 SUB-MODEL 5: BLOCK PROTRUSION

Net uplift pressure coefficients generated by quasisteady flow deviations at protruding rock blocks are mostly situated between 0 and 0.5, depending on the degree of protrusion of the blocks and on the shape of the blocks. For the computations, coefficients of 0.1-0.2 may be considered plausible for low to very low block protrusions, while coefficients of 0.3-0.5 correspond to moderate to significant block protrusions, i.e. for rough and irregular pool bottoms, typically encountered in fractured rock. The latter values are considered most plausible for a real water-rock interface.

The net uplift pressure coefficient is a parameter of the model that has to be calibrated based on the shape and the extent of past scour formation at the site in question.

2.1.6 SUB-MODEL 6: BLOCK UPLIFT

Finally, based on site observations or available geomechanical characteristics of the rock mass, typical rock block shape and dimensions are determined. The shape of the blocks is important because directly related to its ease of ejection. As such, a plate-like shaped block will be easily uplifted by the impacting flow, while a high and short block that is profoundly anchored into the rock mass will be ejected with much more difficulty.

Block stability under quasi-steady flow impact is computed by defining the net uplift forces that may act on a representative rock block during jet impact. The forces are determined by multiplying the net uplift pressure coefficient (§ 2.1.5) with the local kinetic energy of the wall jet (§ 2.1.4) being deviated by the protruding block.



Figure 5: Step-by-step methodology of quasi-steady impulsion (QSI) computations, using a series of 6 sub-models.

3. Case studies

The presented approach has been applied to several rock scour problems worldwide. Two case studies are presented here more in detail: Scour potential in the unlined stilling basin downstream of Bluestone Dam, West Virginia, US, and reconstitution of the scour history of the well-known scour hole downstream of Kariba Dam, Zambia-Zimbabwe.

3.1. Bluestone Dam

Bluestone Dam is a 55 m high concrete gravity dam situated on the New River outside Hinton, West Virginia, US (Figure 6). The dam has been constructed in the 1940's and contains 21 crest gates and 16 sluice gates, transferring the PMF event of 12'200 cms into a 240 m wide by 60 m long downstream stilling basin area that is unlined.



Figure 6: Bluestone Dam (courtesy of USCE, Huntington District)

Current USACE criteria require that the design flood be based on the Probable Maximum Flood (PMF) updated by using the latest hydrology of the catchment area. This condition is expected to produce a PMF of about 25'000 cms in the spillway area, i.e. a doubling of the initially adopted value.

Hence, the downstream stilling basin being basically designed to withstand a much lower flow rate, the scour potential in the stilling basin rock bottom has to be reassessed.

3.1.1 Turbulent flow structure in the stilling basin

The turbulent flow structure responsible for the scour potential in the stilling basin is influenced by the following structural elements: the main dam toe apron containing two rows of baffle blocks and an end sill, the unprotected rock bed forming the stilling basin bottom and finally the downstream end weir.

For increased PMF flow rates, the flows issuing from the dam toe apron impinge the downstream part of the stilling basin rock bed under a very shallow angle. The presence of the end weir deviates part of this flow vertically towards the rock bed. At this location, after impingement, a strong flow return current is generated along the rock bed towards upstream. This return current mixes with the incoming shallow turbulent jet before reaching the dam apron.

As such, potential for regressive scour towards the dam apron may be significant and has been checked for by the Comprehensive Scour Model. The fracture mechanics and block uplift methods have been used to assess the scour potential of the rock bed at the location of flow impingement, i.e. just upstream of the end weir. This area is directly impacted by the turbulent shear layer of the jet diffusing through the pool depth and thus controls the ultimate scour depth of the whole stilling basin area. Both rock break-up methods are particularly suited at this location, but unfortunately do not allow predicting the evolution of the scoured rock bed towards upstream (regressive scour).

Hence, the presented Quasi-Steady Impulsion method has been used to assess the regressive scour potential generated by the flow return current (or wall jet) along the rock bed.

3.1.2 Calibration of the regressive scour potential

As mentioned before, the quasi-steady impulsion method needs to be calibrated. At Bluestone Dam, historically observed scour regression of the rock bed at high flow rates is not available. The only scour observed in the past is very local and generated by very small flow rates during an overflow event in 1996.

Hence, calibration has been performed based upon a 1:35 scaled laboratory model study performed at the Engineering Research and Development Center (ERDC) in Vicksburg, US. ERDC studied the regressive scour potential of the stilling basin by representing the rock mass by large gravel stones. The fracturing stage of the rock mass is thus considered complete, which, based on the available geomechanical characteristics, is a rather conservative but still plausible assumption.

Figure 7 schematically illustrates the equilibrium bottom profile that has been observed during laboratory model experiments for the NEW PMF event of 25'000 cms. The bottom profile has its deepest point of scour next to the end weir, followed by a gradually higher rock bed towards the dam apron.

By appropriate calibration of the main parameters of the QSI method, and by combining the result with the fracturing and block uplift methods, a very similar equilibrium bottom profile is predicted by the numerical model. The geomechanical characteristics used for these computations are very conservative and consider the rock mass as completely broken up and highly fractured into small layers, i.e. extremely scour vulnerable. As such, the similarity with the physical model using downscaled gravel stones is not so surprising.

Second, by assuming less conservative and more reasonable (average) geomechanical characteristics for the rock bed, the numerical model still predicts significant scour potential just upstream of the end weir. Nevertheless, this scour remains local and is not able to regress towards the upstream dam apron.

In the same manner, Figure 8 schematically illustrates the equilibrium bottom profile that has been observed during laboratory model experiments but for the initial PMF event of only 12'200 cms. Again, excellent similarity is observed between numerical computations and physical model results. For this event, the parametric assumptions on the rock mass quality made during the numerical computations clearly have less influence than for the new PMF event. As a conclusion, the QSI method may be considered soundly calibrated because in excellent agreement with the physical model gravel stone experiments, when using similar (very conservative) geomechanical settings in the numerical model. This has allowed to use this regressive scour method to develop time-dependent scour predictions in the whole stilling basin area during extreme flood events and by using different sets of reasonable hydraulic and geomechanic parameters.



Distance

Figure 7: Schematic scour potential in the stilling basin downstream of Bluestone Dam (US): comparison between physical model measurements and numerical computations for several parametric assumptions on the rock mass quality (source: ERDC, Vicksburg). Valid for NEW PMF EVENT (25'000 cms).



Distance

Figure 8: Schematic scour potential in the stilling basin downstream of Bluestone Dam (US): comparison between physical model measurements and numerical computations for several parametric assumptions on the rock mass quality (source: ERDC, Vicksburg). Valid for initial PMF EVENT (12'200 cms).

3.2. Kariba Dam

Kariba Dam is a 128 m high double curvature arch dam located on the Zambezi River, at the border between Zambia and Zimbabwe. The dam has been constructed in the late 1950's and is known worldwide for its huge and unprecedented scour hole that extends about 80 m deep in the downstream gneiss bedrock.



Figure 9: Kariba Dam in Zambia-Zimbabwe (photo: AquaVision Engineering)

The dam has 6 flood gates in total, each measuring about 9m by 9m and having a total discharge capacity of 1'500 m³/s.

Kariba Dam has an impressive history of scour formation that is well documented, based on regular bathymetric operations since 1960 and precise records of all gate operations.

Hence, the scour history of the dam is particularly well suited to perform a complete and long-term calibration of the present QSI method. For this, the numerical computations have been initiated for a perfectly flat rock bottom, representing more or less the initial state immediately after dam construction.

The 2D jet diffusion model incorporated in the CSM allows defining at each point of the numerical grid the turbulent pressure fluctuations acting along the waterrock interface, as well as the flow velocities of the wall jets initiating from the jet's stagnation point and extending along the up-and downstream faces of the plunge pool scour hole. Also, the CSM automatically adapts the pressures and velocities at each grid point during the scour process.

Figure 10 illustrates that sound calibration of the main model parameters allowed the numerical model to correctly predict the scour hole evolution since 1960. Bathymetric surveys and numerically computed scour hole profiles show good agreement.



Figure 10: Detailed scour evolution of Kariba Dam plunge pool since 1960: comparison between bathymetric surveys and numerical computations using the QSI method.

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