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Plunge Pool Rock Scour Assessment by Fluid-Solid Coupling

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Abstract: This paper presents a novel approach for detailed 2D numerical assessment of rock scour in plunge pools or unlined channels downstream of hydraulic structures. The approach is based on an automated coupling between the 3D hydraulics and the turbulence of an impacting jet (or any other turbulent flow environment) and the detailed bathymetric evolution with time of the rocky bottom that is being scoured, for a given flood event. Detailed flow hydraulics are thereby computed by the FLOW-3D® CFD software, allowing sound implementation of air entrainment and defining the main flow parameters at the water-rock interface. Bathymetric evolution with time of the eroding rock mass downstream of the hydraulic structure is computed by the rocsc@r® software, a cloud-based digital tool implementing the latest and most widely used computational methods for scour prediction. This novel fluid-solid interactive approach has been tested and applied to large-scale laboratory experiments of scour hole formation in broken-up rock, generated by rectangular-shaped oblique jets impinging in a plunge pool made of cobblestones, performed at the laboratory of the Civil Engineering Department at Stellenbosch University, South Africa (Bosman and Basson (2020), Bosman (2021)). The scour formation observed during the experiments has been reproduced by the FLOW-3D®-rocsc@r® numerical coupling. Benefitting from a dedicated, user customizable and fully automated interface between both software programs, this coupling requests only very short computational times and constitutes a cutting-edge tool available to engineers for real-life applications and projects. The results obtained for different computational methods of scour formation and a set of CFD modelling parameters are pointed out.

Keywords: fluid-solid coupling, novel software, plunge pool, rock scour

1. Introduction
Rock scour downstream of high-head dams and in unlined channels and stilling basins is more and more frequent. Climate change and related regulatory requirements generate more frequent functioning of dam spillways. Hence, unlined rock masses experience more action of hydrodynamic pressures. Sound prediction of rock scour potential becomes increasingly pertinent, especially for cases where the scour may potentially regress towards the dam.

This paper presents a novel digital software platform that has been developed with the aim to bundle and offer to its users the current state-of-the-art in the field of numerical predictions of scour of rock downstream of dams and in unlined channels and stilling basins. Users will be able to apply and compare a wide range of proven as well as new methods within one single numerical environment, based on user-defined tailored parametric settings of the dam, the turbulent flow and the rock mass.

Moreover, a novel digital database platform has been developed complementary to the software platform, allowing to freely consult any type of worldwide rock scour case studies that have been performed and published, either real-life or laboratory generated. As such, this platform aims at offering a practical and continuously updated database with the potential of informing specialists and engineers on the most relevant results, parameters and calibrations that have been used for each of the available scour computational methods.

The platform focuses on enhancing parametric pertinence and experience. It aims widespread distribution and exchange, so that shared benefits may be expected.

It is believed that this is the first attempt in this field to combine on one single digital platform both powerful and cutting-edge computational potential and directly related up-to-date database availability of published practical experiences and results.
2. The rocsc@r® cloud

2.1. General

The rocsc@r® cloud contains two digital platforms: X_pl@re is a licensed computational platform, while X_ch@nge is a free database platform (Bollaert, 2021). Both platforms solely offer web-based remote access and storage. Cloud users benefit from personalized data encryption. Data results can be stored on user-specific allocated space in the cloud, or on the user’s local IT infrastructure.

X_pl@re comprises the rocsc@r® software, i.e. a suite of the latest computational methods for numerical prediction of rock scour downstream of dam spillways and in unlined channels and stilling basins. The range of methods covers both oblique and vertical impingement of turbulent jets, and is compatible with any other turbulent flow at the water-rock interface, such as free surface flows and hydraulic jumps. X_ch@nge offers a free-access database platform for any type of publicly available rock scour cases at hydraulic structures. For each case, specific geometric, flow and rock mass parameters are provided, in parallel to the observed or computed scour for the related flow event.

2.2. Computational methods

The rocsc@r® software contains both novel and existing computational methods, expressing the different break-up mechanisms of fractured rock masses. Moreover, these methods have been implemented such that users may freely customize the related parameters and equations. The following methods are currently available:

- **Empirical equations**: A wide range of well-known empirical formulae are available. These formulae distinguish between a generic formula that can be user-defined, and more general and simplified formulas (Castillo and Carrillo 2017). More information can be found in Bollaert (2021).

- **Erodibility Index method (EIM)**: The Erodibility Index Method is based on Kirsten’s ripability index and has been adapted by several researchers to scour in unlined plunge pool and stilling basins, based on a large dataset of case studies. This method relates the energy dissipation rate or stream power to the resistance of the rock as expressed by the erodibility index (EI), i.e. a geomechanical index incorporating the mass strength and different characteristics related to the size of the block, the joint roughness and alteration, and the structure of the discontinuities. Information can be found in Bollaert (2021).

- **Dynamic Impulsion methods (DI/MDI)**: The DI method developed by Bollaert and Schleiss (2005) considers the maximum dynamic impulsion underneath a rock block, obtained by time integration of the pressure forces under and over the block, of the immersed weight and of shear forces on the block. The net uplift impulsion considers a time duration of forces and uses a net uplift coefficient Cup [-] determined based on large-scale...
laboratory experiments. Second, the MDI method developed by Bollaert (2021) uses similar physics of block uplift but computes the net uplift force as a function of the RMS values of the pressure fluctuations at the block upper surface and a multiplication coefficient based on large-scale 3D block uplift experiments. Both methods express block failure by comparing the vertical block displacement to the block height.

- **Dynamic Pressure method (DP):** Bollaert (2021) developed a 2D implementation of the block uplift method developed by Maleki and Fiorotto (2019). This method determines the net uplift force on a block based on analytical determination of jet characteristics, as well as by accounting for the RMS coefficient of pressure fluctuations at the block upper face multiplied by a surface reduction coefficient. This approach defines the necessary thickness for a block to be stable, accounting for its submerged weight.

- **Quasi-Steady Impulsion methods (QSI/MQSI):** The QSI method developed by Bollaert (2012) computes the scour potential by detachment or peeling off of protruding rock blocks, due to wall jet flows deviated by such blocks at the water-rock interface and generating quasi-steady lift forces on the blocks. The MQSI developed by Bollaert (2021) extends the previous method for both circular and rectangular jets and obliquely impinging jets, and allows to compute both quasi-steady and fluctuating detachment forces. The related lift forces are defined by an uplift coefficient \( C_p \). The stability of the block is expressed by a force-balance equation.

- **Comprehensive Fracture Mechanics method (CFM):** This method developed by Bollaert and Schleiss (2005) computes progressive fracturing of existing joints in rock masses as a function of time, based on linear elastic fracture mechanics theory and the cyclic character of dynamic pressures generated by turbulent flows. The method expresses scour evolution as a function of time.

2.3. Plunging turbulent flows

The hydraulic parameters of 2D plunging turbulent flows (Fig. 1) are determined analytically along the initial water-rock interface. This process is repeated for similar fictitious interfaces that are progressively situated further downwards, increasing the total tailwater depth, vertically down into the rock mass. The obtained values with depth are stored as 2D matrices. The analytical equations make the assumption of a quasi-horizontal and quasi-flat interface between the rock and the water, without any perturbing elements or suddenly changing interface shapes.

![Figure 2. Sketch of obliquely plunging turbulent flow diffusing through plunge pool and impacting the water-rock interface (source: rocsc@r® Technical Manual, AquaVision Engineering 2022)](image-url)
The hydraulic parameter values stored in the 2D matrices cannot be adapted during the computations as a function of the scour development, and are only applicable for simplified interfaces that respect the assumptions upon which the analytical equations are based. Use of predefined 2D matrices is strictly speaking only valid for cases where the change in interface shape has no significant influence on the hydraulic parameter values that were defined at start.

The analytical equations describing plunging turbulent flows allow predefining and storing the values of the main hydraulic parameters in 2D matrices. These matrices respect the network of computational nodes of the 2D vertical profiles, along which the scour computations are being performed (Fig. 2). As such, in every computational node, the hydraulic parameters that are needed for the scour computations are being predefined before start. The corresponding values account for the progressively increasing flow depth during scour formation. The following hydraulic parameters are predefined with depth and stored in 2D matrices, based on analytical solutions of the flow environment:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$</td>
<td>Mean dynamic pressure coefficient</td>
</tr>
<tr>
<td>$C_{p}'$</td>
<td>Fluctuating (RMS) dynamic pressure coefficient</td>
</tr>
<tr>
<td>$C_{\text{max}}$</td>
<td>Maximum dynamic pressure coefficient</td>
</tr>
<tr>
<td>$C_I$</td>
<td>Dynamic impulsion coefficient</td>
</tr>
<tr>
<td>VEL</td>
<td>Average flow velocity quasi-parallel to interface</td>
</tr>
<tr>
<td>$SP$</td>
<td>Average stream power at interface</td>
</tr>
</tbody>
</table>

The pressure coefficients have to be multiplied by $\rho V^2/2g$ to obtain the pressure values in [N/m²], and the impulsion coefficient by $\rho AV^2L/c$ to obtain impulsions in [Ns], with $V$ the jet velocity at impact in the pool, $c$ the wave celerity, $L$ the joint length and $A$ the horizontal rock block area. Fig. 3 illustrates an example of the average dynamic pressure coefficient $C_p$ at the interface, due to a rectangular jet impacting the pool under an angle of 70° with the horizontal. The spatial distribution of the pressure at the rock surface is represented by the black curve (right-hand side axis), while the evolution with depth is represented by a graded heatmap (legend on the right).

Similar curves are defined in the model for all hydraulic parameters listed at Table 1. This 2D matrix system covers both circular and rectangular-shaped jets, as well as vertically or obliquely impinging jets for angles between 20° and 90°. Moreover, both compact and broken-up jets are accounted for, as well as the air concentration and degree of break-up of the jets at impact, and the initial turbulence intensity at issuance from the dam.
3. Fluid-solid interactive scour computations

3.1. RemoteSc@r™

RemoteSc@r™ is an API (Application Programming Interface) that offers a dedicated interface between the FLOW-3D® commercial CFD software (Flow-3D, 2019) and the rocsc@r® software. The current version only allows 2D computations, but a 3D version is under development. RemoteSc@r™ allows to perform fluid-solid interactive scour computations by sequential coupling. Fig. 4 illustrates the main parameters to be defined for both software.

![RemoteSc@r™ User Interface](image)

**Figure 4.** User Interface of the RemoteSc@r™ API (RemoteSc@r manual 2022)

3.2. Methodology

The fluid-solid interactive computations follow the following methodology:

1. FLOW-3D® transient simulation to reach a quasi steady-state of main hydraulic parameters at the water-rock interface
2. Transfer of hydraulic parameters to rocsc@r® by use of a generic exchange file (csv format)
3. Computation of scour in rocsc@r® based on a user-defined max. layer or a max. time duration (CFM method)
4. Transfer of scoured water-rock interface to FLOW-3D® by use of a STL-file
5. Repetition of steps 1 to 5 until no further scour occurs anymore
4. Case study

4.1. The Stellenbosch scour tests

Large-scale laboratory experiments of scour hole formation in broken-up rock, generated by rectangular-shaped oblique jets impinging in a plunge pool, have been performed in the laboratory of the Civil Engineering Department at Stellenbosch University, South Africa (Bosman and Basson (2020), Bosman (2021)). This scour formation has been reproduced by the rocscor® software.

![Figure 5. Experimental set-up of plunging jets impinging on broken-up rock bed (Bollaert 2021, adapted from Bosman, 2021)](image)

The physical model is illustrated in Fig. 5 (adapted from Bosman, 2021) and consists of a zero-sloped 0.25 m wide rectangular canal replicating an uncontrolled dam spillway. The canal could be adjusted to three different fixed heights above the movable rock bed: 3, 4 and 5 m (prototype heights for 1:20 model scale: 60, 80 and 100 m). The tailwater depth at the plunge pool was adjustable between 0.5 m and 1 m (prototype: 10 m and 20 m). The plunging jets generated unit discharges between 0.100 and 0.224 m³/s/m (prototype: 35 to 80 m³/s/m).

The broken-up rock bed was modelled by using tightly hand-packed concrete paver blocks (cobblestones), generating a uniform three-dimensional open-ended horizontal and vertical rock joint network. The two rock sizes tested were rectangular concrete pavers with x, y, z dimensions of 0.1 m × 0.1 m × 0.05 m and 0.1 m × 0.1 m × 0.075 m (prototype: 2 m × 2 m × 1 m and 2 m × 2 m × 1.5 m respectively). The paver block densities used were 2’355.4 kg/m³ (for 1m high blocks) and 2’388.1 kg/m³ (for 1.5 m high blocks) respectively. A total of 31 experimental tests were carried out by the authors.

From these, one scour test has been chosen here to be reproduced by the different computational methods that are proposed by the rocscor® software, with and without coupling with the FLOW-3D® CFD software. The test involves a jet velocity at issuance of 12 m/s and a jet thickness at issuance of 6 m, for a tailwater level of 20 m.

4.2. Scour computations without FLOW-3D® coupling

Firstly, the scour computations have been performed without coupling with FLOW-3D®, i.e. by using the 2D flow matrices generated by rocscor® at start of the computations. Fig. 6 illustrates the computed scour for the DI, MDI, QSI and MOSI methods and shows good agreement with the scour observed during the laboratory experiments. Both the deepest scour and the shape of the scour hole are soundly reproduced by the rocscor® software. More details on calibration parameters can be found in Bollaert (2021).
4.3. Scour computations with FLOW-3D® coupling

Next, the scour computations have been repeated by coupling rocsc@r® to FLOW-3D®. The modelling parameters are summarized at Table 2. A Large Eddy Simulation (LES) turbulence model has been used, for a mesh size of 0.5 m. Furthermore, the model incorporates air entrainment of the jet and the plunge pool, as well as related flow bulking. The surface roughness height of the rock was defined at 1 m, which corresponds to plausible estimates given the physical height of the perturbing cobblestones. Values of rock roughness heights for practice would be typically between 0.10 and 1.0 m, depending on the joint sets and typical in-situ rock block heights. A no-slip boundary condition was applied at the water-rock interface.

Fig. 7 illustrates the scour results obtained during consecutive (numbered) iterations between rocsc@r® and FLOW-3D®, as well as the jet trajectory and plunge pool flow velocities computed by FLOW-3D® in a vertical 2D profile. The laboratory observed scour formation is presented by the thick dotted grey line.

For a max. scour value of 1 m per iteration (i.e. equal to the block height) and using the MDI method, good agreement is observed between measurements and computations. Not only the area of deepest scour formation is well modelled, but also the slopes of the scour hole towards upstream and downstream are adequately reproduced. The computation converged in 35 iterations and took 1h45 min. on a standard INTEL i5 processor. The critical net uplift height ratio \(n_b\) equaled 0.20, i.e. within the range of usual values based on experience from practice, but nevertheless slightly higher than the value of 0.10 that was proposed by using the internal 2D flow matrices instead of FLOW-3D®. This is merely because of the slightly different RMS pressure fluctuations and their different vertical decay computed by FLOW-3D®, as compared with the values as provided by internal 2D flow matrices in rocsc@r®.
4.4. Parametric comparison between FLOW-3D and rocsc@r

Finally, a direct comparison has been made of the main hydraulic parameters between FLOW-3D® and the internal 2D flow matrix system of rocsc@r®. The fluctuating part of the dynamic pressures generated by the impacting jet (root-mean-square or RMS values) at the water-rock interface is presented and compared in Fig. 8. The FLOW-3D® computed values are in good agreement with the rocsc@r® computed values at the point of jet impact, but slightly differ outside of this area. The lateral decay of the RMS values at first follows a very strong slope, in agreement with the rocsc@r® analytical values for a concentrated dynamic pressure curve. Next, this lateral decay strongly diminishes and the RMS values remain almost constant with increasing lateral distance from the impact point.
Figure 8. Comparison of RMS pressure fluctuations computed by rocsc@r® and by FLOW-3D®

Figure 9. Comparison of averaged flow velocities at interface computed by rocsc@r® and by FLOW-3D®
The latter behavior is much more in agreement with rocsc@r® values for a strongly dispersed dynamic pressure curve, i.e. for which RMS values remain significant even at large distances. The latter curves are typically observed during laboratory observations involving jet impingement. Moreover, the FLOW-3D® computed RMS values are in excellent agreement with the measurements made by Wei et al. (2020) for a comparable case of an obliquely impinging aerated laboratory jet. The agreement can be noticed by a similar RMS increase at jet impact, and by the quite constant RMS values computed laterally outwards from the point of jet impact, which were also measured during in the laboratory.

Second, Fig. 9 compares the time-averaged wall jet velocities that develop along the water-rock interface following jet impingement. The FLOW-3D® computed velocity curve is of similar shape than the rocsc@r® computed flow velocity curve for broken-up jets and a jet core extension K of 4 times the jet diameter at impact. However, in the area of jet impingement, the FLOW-3D® computed flow velocities are somewhat higher and are situated in between values valid for broken-up and compact jets. Furthermore, the FLOW-3D® computed velocities show a dip at the point of jet impact where significant stagnation pressure builds up. This is logic because this area is not part of the wall jets, that generally start at a lateral distance of 1-2 jet diameters. The rocsc@r® computed velocities do not show this dip because it is automatically removed from the analytical equations for convenience of scour computations.

5. Conclusions

Rock scour computations downstream of hydraulic structures have been performed along vertical 2D profiles by a novel fluid-solid coupling between the rocsc@r® software and the FLOW-3D® CFD software. The former computes detailed 2D rock break-up and scour formation in rock masses with time, based on a large set of computational methods, while the latter computes the 2D or even 3D flow parameters and turbulence at the water-rock interface. Both programs are linked together by using the RemoteSc@r™ API connection benefitting from a dedicated, user customizable interface. This coupling requests relatively short computational times and constitutes a cutting-edge tool available to engineers for real-life applications and projects. Application of this fluid-solid coupling to the laboratory tests of scour performed at the University of Stellenbosch (Bosman & Basson 2020) shows first of all that the observed scour is well reproduced. Furthermore, the hydraulic parameters computed by FLOW-3D® at the water-rock interface are in reasonable to good agreement with the corresponding analytical equations based on 2D jet diffusion theory. This points out the adequacy of the LES turbulence model used by FLOW-3D® to generate these parameters.

6. REFERENCES