SCOUR FORMATION AT BOTTOM OUTLET OF KÁRAHNJÚKAR DAM

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Landsvirkjun, the National Power Company in Iceland, is completing the 690 MW hydroelectric Kárahnjúkar project in eastern Iceland. Main construction started in the springtime of 2003, and full power production was reached in early 2008. The main dam is a 200 m high CFRD dam, (concrete faced rockfill dam), the highest of this type in Europe and one of the highest CFRD dams in the world. The total length of tunneling is about 73 km, of which about 48 km is drilled by three TBM (tunnel boring machines), 7.2 to 7.6 metres in diameter. Total estimated cost of the Karahnjukar project is around 1.1 billion EUR.

The bottom outlet of Kárahnjúkar Dam is 5.2 m wide, 6 m high and is concrete lined. The first 50 m are near horizontal, followed by a sudden slope change down to 5 % for the remaining 300 m downstream. The invert and side walls are concrete lined up to a height of 3.5 m. The cylindrical apex is shotcreted. The tunnel ends with a double curvatured flip bucket that projects the water jet with an angle between 21 and 28° into the downstream canyon. Numerical computations have been performed of potential scour formation of the canyon bottom following bottom outlet operation. Both downstream tailwater level and duration of discharge have been accounted for. The results show that scour formation in the canyon riverbed will remain quite limited. Scour may occur under the form of uplift and displacement of loose blocks that are already present at the riverbed. Subsequent fracturing and block formation of the in-situ rock mass will take considerable time to occur and will most probably not result in excessive scour formation.

Comparison has been made with hydraulic model tests of scour formation and showed very good agreement.

Key Words : *Numerical computations, bottom outlet scour*

1. INTRODUCTION

Landsvirkjun, the National Power Company in Iceland, is currently finishing the 690 MW hydroelectric Kárahnjúkar project in eastern Iceland. Main construction started in the springtime of 2003, and full power production was reached in early 2008. The main dam is a 200 m high CFRD dam, (concrete faced rockfill dam), the highest of this type in Europe and one of the highest CFRD dams in the world. The total length of tunneling is about 73 km, of which about 48 km is drilled by three TBM (tunnel boring machines), 7.2 to 7.6 m in diameter. Total estimated cost for the power project is around 1.1 billion EUR. For more details on the Karahnjukar project, reference is made to the project website: www. karahnjukar.is.

As shown in Figure 1, the bottom outlet of Kárahnjúkar Dam is 5.2 m wide, 6 m high and is concrete lined. The first 50 m are near horizontal, followed by a sudden slope change down to 5 % for the remaining 300 m downstream. The invert and side walls are concrete lined up to a height of 3.5 m. The cylindrical apex is shotcreted. The tunnel ends with a double curvatured flip bucket that projects the water jet with an angle between 21 and 28° into the downstream canyon. The present paper describes numerical computations of potential scour formation in the downstream canyon riverbed following this jet impact during bottom outlet operation.

2. THE SCOUR MODEL

The Comprehensive Scour Model (CSM) has been developed by Bollaert[1), 2)] and Bollaert & Schleiss[3)] and represents a new method to evaluate the ultimate scour and the time evolution of scour in fractured rock. The CSM estimates the ultimate depth of scour but also the time evolution of scour in partially or totally fractured rock or concrete.

The model is physically based and the parameters are defined such that they can be used for engineering practice. This guarantees the comprehensive character of the model, without neglecting basic physics behind it. The scour model consists of three modules: the falling jet, the plunge pool and the fractured rock or concrete. The modules for the falling jet and for the plunge pool define the hydrodynamic loading that is exerted by the jet on the rock mass. The former determines the major characteristics of the jet from its point of issuance at the dam down to the point of impact into the plunge pool. The latter describes the diffusion of the jet through the pool and the resulting jet excitation at the water-rock interface. The module for the rock mass has a twofold objective.

First of all, it transforms the hydrodynamic loading at the water-rock interface into a critical stress inside the rock mass (for closed-end joints) or into a net uplift impulsion (for single rock blocks). Second, it defines the basic geomechanical characteristics of the rock mass, relevant for the determination of its resistance. A more detailed description of all modules can be found in Bollaert [2)]. Two rock mass failure criteria are of importance (Figure 2):

1. Failure of rock joints by break-up of the joints. This can be instantaneous or time-dependent. The latter case involves failure by fatigue. This is expressed by the Comprehensive Fracture Mechanics (CFM) method.

2. Failure of rock joints by dynamic uplift or displacement of the rock blocks. This is expressed in the Dynamic Impulsion (DI) method.

Each failure criterion constitutes a physical limit for development of the scour hole. Which criterion is most restrictive depends on the geomechanical characteristics of the rock mass.

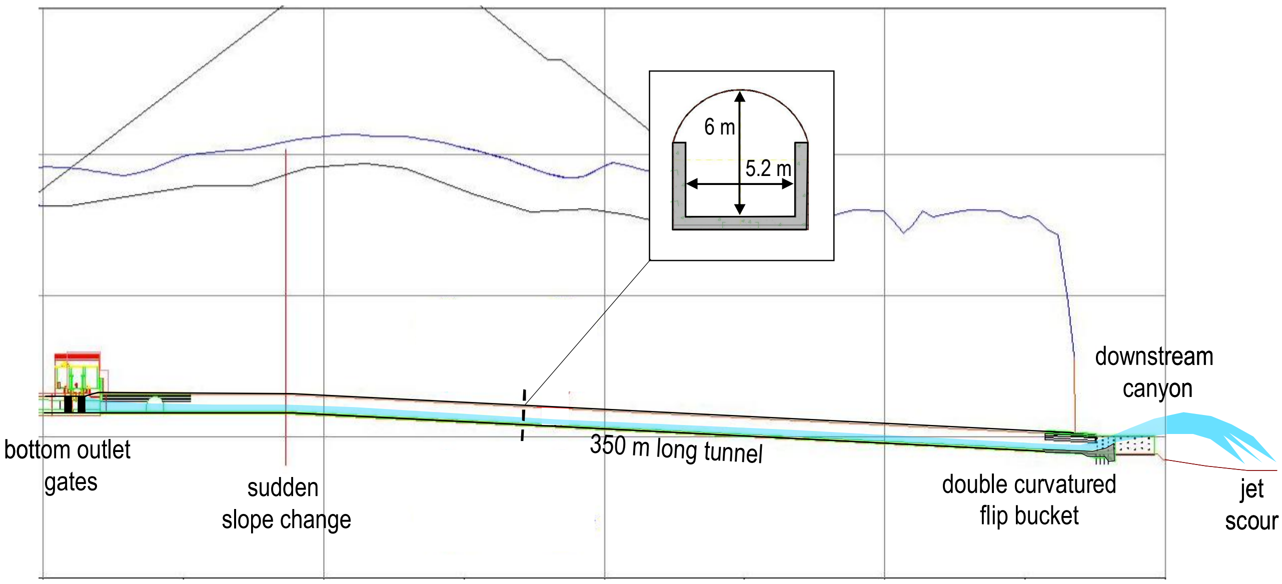

Fig. 1 Longitudinal profile of bottom outlet tunnel and double-curvatured flip bucket

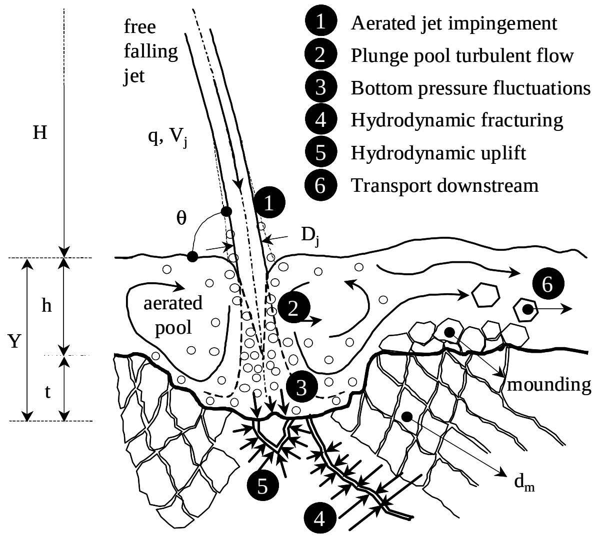

Fig. 2 Sketch of the most important physical-mechanical processes responsible for scour of fractured rock: processes 4 and 5 are dealt with in detail.

3. SCOUR PARAMETERS

The hydraulic parameters have been defined based on an air-water numerical modeling by the Falvey[4] model. Figure 3 shows the water surface elevations throughout the tunnel for a maximum discharge of 360 m^3/s. Flow velocities are around 35 m/s at the flip bucket.

The preliminary estimates of rock properties relevant to scour have been presented in a Field Visit Report of the Spillway Scour (AquaVision Engineering[5]). The rock mass is divided into two principal formations, i.e. the Móberg formation and the underlying UTB basalt. For the present bottom outlet scour formation, only the rocky riverbed is of importance, consisting of UTB basalt. The exact properties of the canyon bed are not known, but are assumed similar to the UTB basalt on the sides of the canyon, as observed for example at the diversion tunnel outlet. This assumption is reinforced by a photo of the dry canyon bed (Figure 4, P. Jóhannesson).

The rock properties distinguish between conservative, average and beneficial engineering assumptions. The different values used have their origin in the uncertainties on measured rock properties or uncertainties related to the application of the scour model.

4. SCOUR RESULTS

Scour computations have been performed for a maximum bottom outlet discharge of 360 m^3/s, corresponding to a maximum reservoir level of 625 m a.s.l. and a 100 % gate opening. Based on scour protection measures projected further downstream in the canyon to cope with spillway jet impact, the tailwater level is defined at max. 452 m a.s.l.

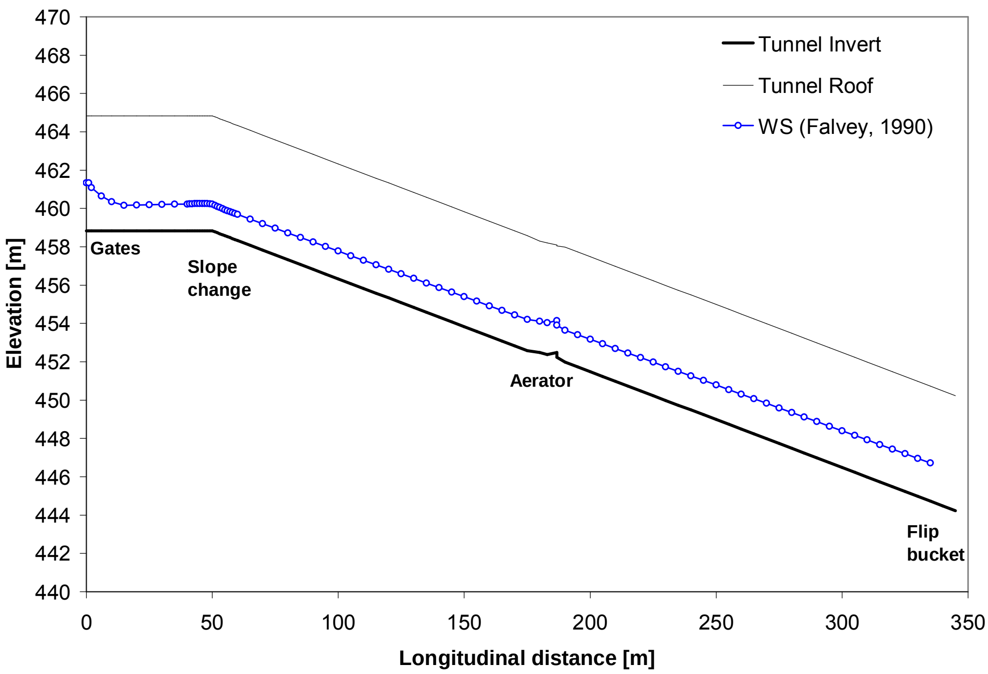

Fig. 3 Water surface elevations along the bottom outlet tunnel (based on Falvey[4])

Fig. 4 View of the canyon with dry riverbed (photo courtesy by P. Jóhannesson)

(1) Issuing jet

The input parameters are defined by the characteristics of the air-water flow at issuance from the bottom outlet (velocity, air entrainment, water depth, shape, angle). The velocity and water depth at issuance have been defined based on two-phase flow assumptions and accounting for Darcy-Weisbach friction losses, curvilinear flow effects at slope changes and the development of a turbulent boundary layer (Falvey[4)]). The design of the flip bucket proposes a varying lip height and angle. As such, as presented on Figure 5a, on the right hand side, the lip height is 1.15 m for a 20° angle with the horizontal. The left hand side proposes a lip height of 2.55 m for a 30° angle. Furthermore, the profile of the flip bucket corresponds to a curved shape with an outlet angle of about 19° (Figure 5b). The present design has been done to prevent the issuing jet from impacting along the left sidewall of the canyon at that location.

The shape of the jet is strongly influenced by the curved shape of the flip bucket. The left hand side of the issuing jet travels much further than the right hand side. This generates a highly diffused jet pattern that impacts the riverbed over a relatively large area.

Hence, for the scour computations, the jet has been subdivided into 3 distinct zones as presented in Figure 5a: the LEFT, MIDDLE and RIGHT zones. Each of these zones is considered to incorporate one third of the total discharge, while the geometric characteristics at jet issuance are computed as an average of the zone of interest.

(2) Jet diffusion in tailwater

The second module describes diffusion of the jet through the downstream water depth, i.e. the natural water depth in the canyon bed for the discharge in question. The diffusion is characterized by turbulent pressure fluctuations and high air concentration. The used water depths are defined at 445 m a.s.l. and 452 m a.s.l. The former corresponds to the minimum possible value because it is the initial canyon riverbed level. This low tailwater level is justified because the jet impacts the riverbed under a very low angle with the horizontal. As such, the dynamic force of the jet is able to push the stagnant water level towards downstream. The latter tailwater level is given by the tailpond dam height that has been designed to prevent spillway scour formation further downstream. It is considered to be the maximum possible tailwater level at the bottom outlet.

(3) Rock mass module

The last module describes the characteristics of the rocky riverbed. A short description is given here on the choice of the values for these parameters.

a) UCS strength

Geologic reports indicate compressive strengths on the order of 60 MPa and higher for the UTB basalt. Large scatter has been observed during point load tests on basalt cores taken at the headrace tunnel more upstream, as well as different results based on the type of testing procedure. An inverse relationship has been pointed out between the porosity and the mass strength of the basalt. Also, very low mass strengths were attributed to the possible presence of scoria in the upper and lower parts of the basalt layer.

Field observations indicate low strengths of the weathered basalt along the canyon walls (on the order of 20 to 40 MPa). Hence, it is not excluded that the basalt formation at the flip bucket contains scoria. Borehole investigations indicated that 80% of the layer thickness contains scoria and is of vesicular character. Therefore, for the scour computations, a conservative approach leads to a UCS value of around 20 MPa, while a beneficial assumption corresponds to values around 140 MPa. In between, an average value has been defined at 80 MPa.

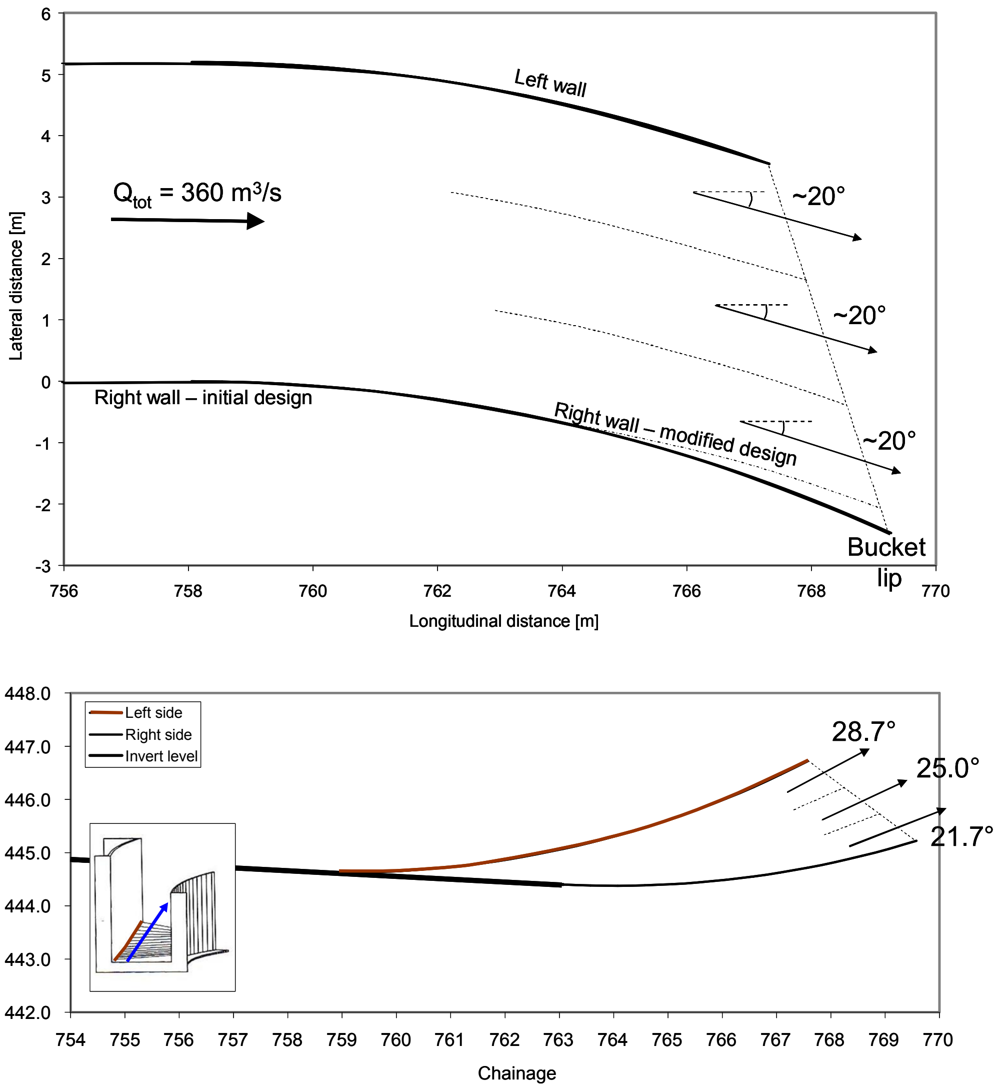

Fig. 5 Design of flip bucket: a) Plan view; b) Longitudinal profiles.

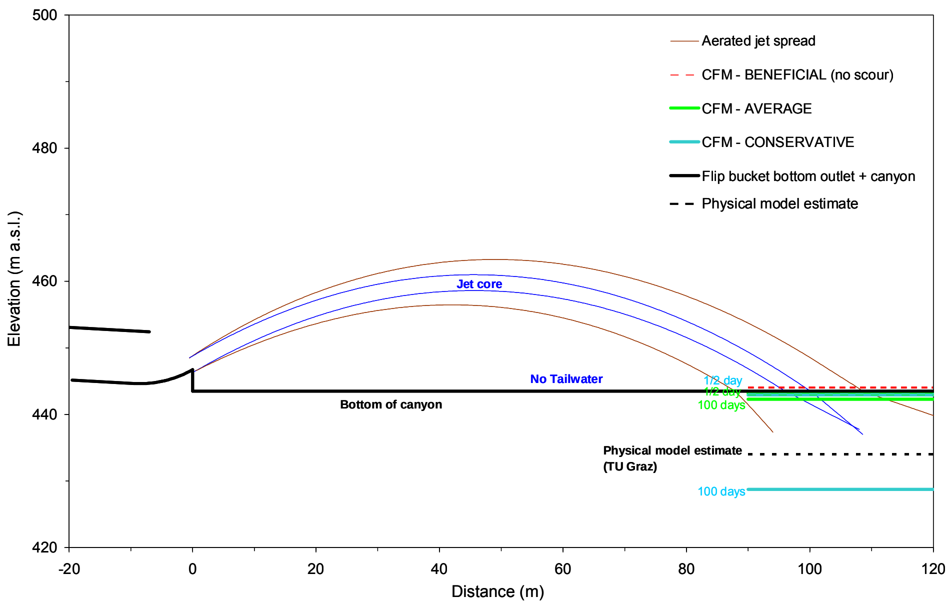

Fig. 6 Jet trajectory and scour formation in riverbed as a function of time duration of discharge (only CFM model): the LEFT hand side of the jet (largest trajectory distance). Comparison with physical model estimate of deepest scour in canyon.

CFM method					DI method			
TIME		BENEF	AVER	CONS	TIME	BENEF	AVER	CONS
Days	Hours							
0.5	**12**	443.2	443.2	443.2	**infinity**	435.7	433.8	432.9
1	**24**	443.2	443.2	443.2				
4	**96**	443.2	443.2	442.9				
10	**240**	443.2	443.2	442.0				
50	**1200**	443.2	442.9	429.0				
100	**2400**	443.2	442.3	428.7				

Table 1 Scour formation as a function of time duration of discharge computed based on the CFM and the DI methods: the LEFT hand side of the jet (largest trajectory distance).

b) Density of rock

The density of the rock mass has been defined based on performed testing. The values fluctuate between 2700 and 2900 kg/m^3.

c) Ratio of horizontal/vertical stresses

The ratio of horizontal to vertical stresses (K_0) has been defined based on hydraulic jacking tests. The results indicate minimal horizontal stresses on the order of 1.5-1.8 MPa at the depth of the canyon bed (440-420 m a.s.l.). This corresponds to K0 values of 2-3.

d) Typical maximum joint length

The typical maximum possible joint length is theoretically defined by the estimated joint spacing. For practice, a value of 1m is often assumed. Lower values prevent pressure amplifications from occurring inside the joints, while higher values are often improbable due to a high degree of jointing of the rock.

e) Vertical persistency of joints

The persistency of the rock joints represents the initial degree of break-up of the joints, i.e. the actual joint length divided by the maximum possible joint length once the joint network is completely formed. Values are defined based on practical experience. They depend on the tightness of the joints, the UCS strength and the number of joint sets.

f) Form of joints

The form of the rock joints distinguishes between circular, elliptical and single-edged joints. The former benefit from a high lateral support from the surrounding rock mass, while the latter has quasi no lateral support and thus results in a conservative approach.

g) Tightness of joints

The tightness of the joints determines the capability of the jet to generate severe pressure amplifications and fluctuations inside the joints. Very tight joints will be able to generate high pressures, while open joints are not able to amplify the impacting jet pressures.

h) Fatigue parameter of joints

The joint wave celerity, fatigue sensitivity and fatigue coefficient are parameters that describe the time evolution of scour. The former parameter has been defined based on prototype-scaled experiments of transient pressure waves inside simulated rock joints (Bollaert[1)]). The fatigue sensitivity and coefficient are values that have been defined in the field of fracture mechanics of rock and concrete material, mainly based on laboratory fracturing tests. Appropriate calibration of these values has been performed in Bollaert[1)]).

i) Number of joint sets / block dimensions

The number of joint sets defines the persistency of the joints and their sensitivity to break-up. It also allows defining the general shape and dimensions of the rock block that is considered characteristic for the whole broken up rock mass. These block characteristics are used in the Dynamic Impulsion Method to estimate the net uplift forces on a single rock block as a function of depth.

(4) Computations for NO tailwater depth

The results of the scour computations are summarized at Table 1 and in Figure 6 for the LEFT (largest trajectory) hand side of the jet (only CFM results). The tailwater depth imposed by the river has (safely) been neglected. It can be observed that the ultimate scour depth is estimated at 438 m a.s.l. (CFM) or 435 m a.s.l. (DI) for average parametric assumptions. When considering conservative (safe-side) assumptions, the maximum computed scour elevation is 430 m a.s.l. (CFM) or 434 m a.s.l. (DI). The DI model results are very close to the deepest scour elevation of 434 m a.s.l. measured during hydraulic model tests performed at Graz University of Technology (TU Graz[6)]). These tests were also performed with loose granular material.

Secondly, the RIGHT hand side of the jet results in an ultimate scour depth of 436 m a.s.l. (CFM) or 438 m a.s.l. (DI) for average parametric assumptions. When considering conservative (safe-side) assumptions, the maximum computed scour elevation is 434 m a.s.l. (CFM) or 437 m a.s.l. (DI).

Finally, for a 452 m a.s.l. tailwater depth, computed scour was considered negligible, regardless of the parametric assumptions or the jet trajectory.

5. CONCLUSIONS

Scour formation in the downstream canyon riverbed has been computed based on fracture mechanics (CFM method) and dynamic impulsion of single blocks (DI method). The computations have been performed for two extreme tailwater situations: no tailwater depth and a maximum depth of 452 m a.s.l., and for three different parametric assumptions: beneficial, average and conservative assumptions. The jet issuing from the flip bucket has been subdivided into three separate flows. This allowed accounting for the variable issuance angle and lip height of the flip bucket.

For no tailwater depth and along the largest jet trajectory (left hand side), the CFM method only indicates scour in case of conservative assumptions, with a maximum scour depth of about 13 m after 100 days of discharge. The DI method computes potential ultimate scour of 7 to 10 m deep, depending on the parametric assumptions.

For no tailwater depth and along the smallest jet trajectory (right hand side), the CFM method only indicates scour in case of conservative assumptions, with a maximum scour depth of about 11 m after 100 days of discharge. The DI method computes potential ultimate scour of 6 to 8 m deep, depending on the parametric assumptions.

Finally, for a 452 m a.s.l. tailwater depth, computed scour was considered negligible, regardless of the parametric assumptions or the jet trajectory.

As a summary, it can be stated that scour formation in the canyon riverbed will remain limited. When scour is predicted, this will most probably occur under the form of uplift and displacement of loose blocks that are already present at the riverbed. Subsequent fracturing and block formation of the in-situ rock mass will take considerable time to occur and will most probably not result in excessive scour formation.

The present computations have been performed based on rock quality estimates taken from borehole investigations at other site locations (at dam, tailrace tunnel, etc.). A more precise and reliable estimate would need detailed information on the rock mass characteristics at the point of jet impact.

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