ESTIMATION OF SCOUR EXTENT DOWNSTREAM OF AN ARCH GRAVITY DAM CONSIDERING THE TIME EFFECT CASE STUDY: SALMAN-FARSI PROJECT

S. TALEBI

Mahab-Ghodss Consulting Engineers
Tehran, Iran

H.E. MINOR

Laboratory of Hydraulics Hydrology and Glaciology (VAW)
Swiss Federal Institute of Technology Zürich (ETH)
Zürich, Switzerland

CH. ORTMANNS

Laboratory of Hydraulics Hydrology and Glaciology (VAW)
Swiss Federal Institute of Technology Zürich (ETH)
Zürich, Switzerland

In this article, rock scouring downstream the spillway of Salman-Farsi Dam, currently under construction in Iran, is studied. This dam with a gated spillway has a height of 132 m and 1400 million m^3 of reservoir volume. The curved spillway contains three main bays with eight radial gates combined, ending in a ski jump. The hydrological and the hydraulic analysis have been carried out to define the design floods and the kinetic energy of the water jet at the flip bucket. The results of the hydraulic model have been utilized to define the jet pattern. By selecting the most reasonable relation for scour prediction; the maximum and the probable scour extent have been estimated taking the geological situation downstream the spillway into account. Furthermore the time development of the scour has been estimated.

1 Introduction

High velocity plunging water jets, which occur downstream of dams and spillways, can erode the river bed. The designer's main concern is usually to have the impact zone as far as possible away from the structures to protect the foundation against erosion. The spillway ending in a flip bucket is widely used for this purpose in different large dams.

During the jet trajectory to its impact location, extremely turbulent flow exists and the jet spreads and frays. A portion of the jet energy is dissipated by the interaction of the water and the air boundary resulting in considerable spray. The impact of the jet is considerable even if the downstream bed material is rock. Certainly, major scour holes are formed in massive hard rocks as well as in alluvial soil. Their development is often rapid and depends more on hydraulic factors than on geological ones. The jet trajectory distance depends on the velocity of flow entering the flip bucket, the trajectory angle, and the vertical distance from the bucket lip to the impact area. In most of the cases prototype trajectories are somewhat shorter and have steeper impact angle than the model or theoretical jet due to the greater air resistance encountered in the prototype.

2 Description of Salman-Farsi Dam project

Salman Farsi (Ghir) Dam, currently under construction, is located at the entrance of the Karzin Gorge on the Ghare-Aghaj River approximately 180 km South East of the city of Shiraz in Iran, 20 km north east of (Salman Farsi) Ghir city.

This dam with a gated spillway has a height of 132 m and 1400 million m^3 of reservoir volume. The spillway, contains 3 main bays with together 8 radial gates ending in a ski jump, which has a curved shape, Figure 1.

The dam is situated in the folded belt of the Zagross mountain gorge. The rock mass of dam site is heterogeneous and the dam is founded on an Asmari limestone formation, which in the project area consist of lower, middle, and upper members. The type of rock in plunge pool area downstream of spillway is middle Asmari formation varied from calcarenite to cherty limestone. (Fouladi & Golshan 1999)

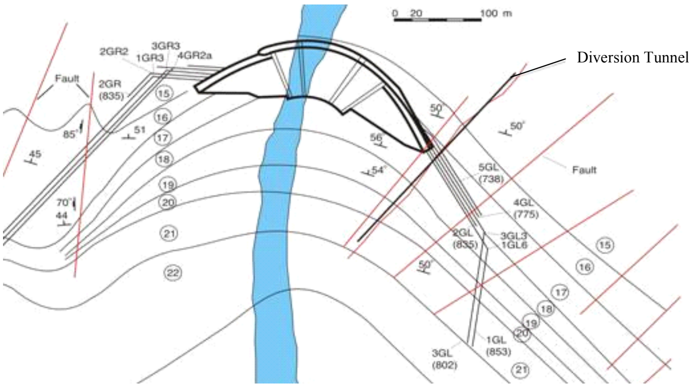

Figure 1. Simplified geological layout of the dam site

3 Methodology

In this study the following procedures and analysis have been performed:

- Conducting hydraulic analysis for different floods and special cases to determine the velocity and water depth at the lip of flip bucket.
- Simulating the hydraulic model to define the shape, the length and the impact width of water jet using the photos of the jet trajectory in Model.
- Determining the maximum and the proable depth and extent of the scour hole using the selected formulas, by means of the results of model simulation and considering the time effect.

3.1. Hydraulic analysis

The hydraulic analysis is performed in order to obtain the kinetic energy of the water jet at the lip of the flip bucket. In addition to normal cases including the different floods when all gates are opened, the special cases of spillway operation are considered, in which some gates are closed. The calculated velocity and the water depth at the lip of the flip bucket are within the range of 22 m/s and 0.50 m for 2 year return period flood and, 32.6 m/s and 8.77 m for PMF.

3.2. Model Simulation

Because of the curved shape of the spillway in Salman-Farsi Project, in addition to the velocity and the energy head of water jet, the pattern of jet trajectory in the air has also influenced the impact width. In this study, the jet trajectory pattern has been predicted by simulating the results of the hydraulic model test.

The hydraulic model of the spillway, with the scale 1:55, is actually tested in Iran. The scour tests have not been performed yet. The main parameters such as the width of jet at the conjunction point of the jets through out from the middle and side bays, the impact width of water jet on tailwater, the location of conjunction point of the middle and side jets and the total length of water jet until tailwater level are measured from the photos of the model tests, as shown is Figure 2.

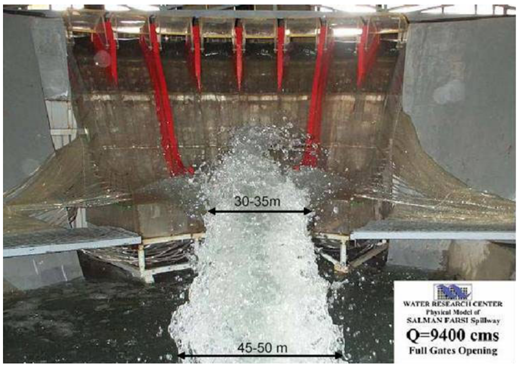

Figure 2. Measuring the jet pattern from Hydraulic Model

The model investigation results are displayed in Table 1.

Table 1. Results of the model investigation

Q (m^3/s)	R.W.L. (m.a.s.l.)	T.W.L. (m.a.s.l.)	b_o (m)	b_1 (m)	b_{impact} (m)	L_1 (m)	L_2 (m)	L_1 / L_2	δ_s (°)	δ_m (°)	θ_o
13’569	934.37	861.1	---	35	---	---	80-85	---	1.4	1.8	8° to horizontal
9’400	931.16	856.9	---	30-35	45-50	35	80	43%	1.3	1.7	7° to horizontal
500	930.00	837.6	4	25	8-10	35-40	60	67%	1.1	1.4	7° to flow direction

* ’δ_s’ and ‘δ_m’ are, respectively, the side and the middle spread angles; all the parameters in this Table are shown in Figure 3.

The following results are derived from model investigation:

- With increasing discharge, the conjunction point of the water jets from the middle and the side bays becomes closer to the bucket and L_1/L_2 decreases.

- With increasing discharge, the water jet spreads more, thus δ increases.
- The jet through middle bay spreads more than the jet through side bay. The jet spread angle for the middle bay is within the range of 1.4 to 1.8 degrees, about 2.5-3%, and for the side bays is within the range of 1.1 to 1.4 degrees, about 2-2.5%.
- The combined jet strongly spreads in the air after conjunction of the water jets from middle and side bays.
- The length of the jet obtained from the model observation is about the length derived from Kawakami formula (Whittaker & Schleiss 1984).

After estimating the main parameters for Model, the same parameters are described for the prototype, see Table 2. Considering the air resistance in the prototype; the spread angle of jet, δ, is predicted 25 percent more than the model. Then δ for side bay is considered in the range of 1.4 to 1.8 degrees about 2.5-3%, and for middle bay in the range of 1.7 to 2.2 degrees, about 3-4 %. This range is also adapted with the roughly turbulent jet proposed by Ervine (1987). The length of the water jet is defined by Kawakami formula (Whittaker & Schleiss 1984). For instance; the proposed jet pattern of PMF in Salman-Farsi Project is shown in Figure 4.

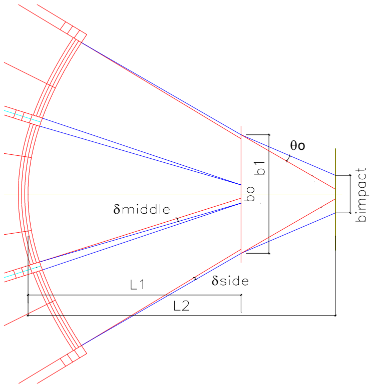

Figure 3. General sketch of jet pattern

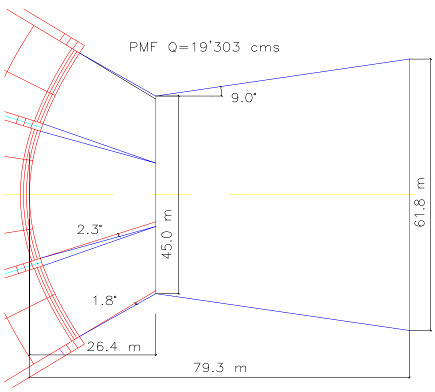

Figure 4. Proposed water jet pattern for PMF

Table 2. The predicted jet pattern for the prototype

Flood	Q (m^3/s)	R.W.L. (m.a.s.l.)	T.W.L. (m.a.s.l.)	L_1 (m)	L_2 (m)	L_1 / L_2	δ_s (°)	δ_m (°)	b_{impact} (m)	q_{impact} ($m^3/s/m$)	L_{total}* (m)
PMF	**19'303**	**937.9**	**864.0**	**26.4**	**79.3**	**33%**	**1.8**	**2.3**	**62.0**	**311.3**	**115**
10'000 yr	**13'760**	**934.4**	**861.1**	**27.0**	**81.8**	**33%**	**1.7**	**2.2**	**59.0**	**233.2**	**112**
1'000 yr	**9'348**	**931.2**	**856.9**	**28.7**	**82.1**	**35%**	**1.6**	**2.1**	**55.0**	**170.0**	**110**
50 yr	**3'960**	**930.0**	**847.6**	**29.7**	**82.2**	**36%**	**1.6**	**2.0**	**52.0**	**76.2**	**104**
Q=500 (m^3/s)	**500**	**930.0**	**837.6**	**34.0**	**59.3**	**57%**	**1.4**	**1.7**	**13.0**	**38.5**	**73**

The ultimate scour depth for different floods is calculated by Machado-A formula. Damle-C and Jaeger formulas have been considered as a lower and un upper limit to define the scour depth. The predicted scour depths calculated by these formulas are shown in Table 3. The grain size for d_m and d_{90} are considered 0.35 and 0.65 meter, respectively.

Table 3. The predicted ultimate scour depth d_S (t+h) in terms of meter

Flood	Q (m^3/s)	Damle - C $0.362\ q^{0.50}\ H^{0.50}$	Machado – A $1.35\ q^{0.50}\ H^{0.3145} / d_{90}^{0.0645}$	Jaeger $0.6\ q^{0.50}\ H^{0.25}\ (h / d_m)^{0.333}$
PMF	**19'303**	**50.3**	**89.7**	**149.8**
10'000 yr	**13'760**	**43.7**	**77.9**	**127.9**
1'000 yr	**9'348**	**37.8**	**67.0**	**104.5**
50 yr	**3960**	**25.9**	**45.5**	**66.4**
Q=500 (m^3/s)	**500**	**16.4**	**30.1**	**43.1**

3.3. Time effect

The ultimate scour depth, derived from different formulas happens after a long duration of spillway operation, mainly depending on the quality and jointing of rock mass. Since plunge pool scour 't + h' is known to develop at an exponential rate with time 'T', the scour rate can be estimated with the following equation:

$$d_s(T) = d_e(1 - e^{-aT/T_e})$$

where 'T' is time, 'T_e' is the time at which equilibrium is attained and 'a' is the site-specific constant. As a rough estimation based on some prototype data, ultimate scour is normally attained only after T_e = 100 to 300 hours of spillway operation (Schleiss 2002). To define the suitable scour rate, the site-specific parameter has been calculated by the authors of this paper in another research. The analysis has been done based on the results of the scour test of Gojeb Project, carried out by Greil (2003). The result of this research shows that 'a=13' has a good adjustment to the scour test results.

4 Results

To define the scour depth and the scour extent in the Salman-Farsi Dam Project, and by reviewing the results of flood routing, hydraulic analysis, evaluation of different scour formulas, definition of water jet pattern for prototype derived from 'the Model Simulation Method' - considering the time effect – we establish the following assumptions:

- The Machado-A formula is selected to define the scour depth.
- The Kawakami approach is used to predict the trajectory length.
- The site-specific parameter 'a' is considered '13'.
- The equilibrium time of scour 'T_e' is defined '200' hours.
- The slope angle of the peripheral rock towards the downstream and the upstream of the scour hole is supposed 30^o and the lateral extent slope is considered 3:1 (V:H).

Based on the above assumptions, the predicted scour depths are presented in Table 4.

As can be seen in Table 2, because of the curved shape of the spillway, the impact zones of the different floods are close together and the scour hole created by PMF would be the envelope scour hole of all floods.

Figure 5 shows, the probability of occurrence of different floods during the useful lifetime of the dam, which is 100 years. The scour created by PMF is considered only to control the maximum risk of instability of the dam and its probability is less than 0.1%. Considering an occurrence probability about 18% during the useful lifetime of the dam, which is equal to probability of occurrence of Maximum Design Level of earthquake (MDL), is reasonable to define the probable scour hole. This probability corresponds to the occurrence of a 500-years flood during the lifetime of the dam.

Table 4. Characteristics of the scour hole proposed in Salman-Farsi Project, considering the time effect

Flood	$Q_{outflow}$ (m^3/s)	R.W.L. (m.a.s.l)	T.W.L. (m.a.s.l)	T (hr)	d_e (m)	d_s (m)	scour ele. (m.a.s.l.)
PMF	19’303	937.9	864.0	24	89.7	70.9	793.1
10’000 yr	13’760	934.4	861.1	26	77.9	63.5	797.6
1’000 yr	9’348	931.2	856.9	30	67.0	57.5	799.4
500 yr	7’947	930.0	855.1	33	65.5	57.9	797.2
50 yr	3’960	930.0	847.6	36	45.5	41.1	806.5
Q = 500 m^3/s	500	930.0	837.6	40	30.1	27.8	809.8

* in which ‘d_e’ and ‘d_s’ are, respectively, the ultimate, and the predicted scour depth considering the time effect

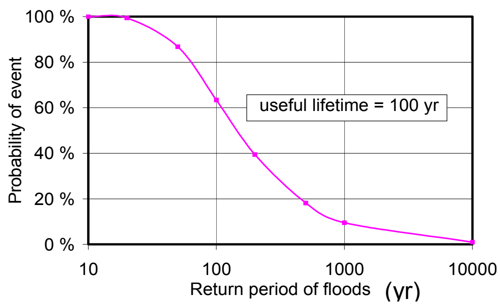

Figure 5. Probability of floods

The maximum and probable scour extents are shown in Figure 6.

5 Conclusion and Recommendation

6.1. *Conclusion*

Machado-A approach was used to predict a reasonable range of scour depth for Salman-Farsi Project. The Damle-C and Jaeger were selected, respectively, as the lower and upper limits to determine the scour depth.

The results of hydraulic model of the Salman-Farsi Spillway were utilized to define the jet pattern for prototype. The results represent a special jet pattern due to the curved shape of the spillway. Regarding to these results, the jet length is almost equal to those derived by Kawakami method.

Based on the results of another research of the authers of this paper, the time effect on the scour depth was considered. According to the results, the scour extent of downstream of Salman-Farsi dam was predicted by Machado-A formula considering T=200 hours and a=13 for different floods. The scour hole for the dam created by PMF is the envelope of all the scour holes. The scour extent of the 500-years flood with an occurrence probability of 18% is predicted as a probable scour hole in this project.

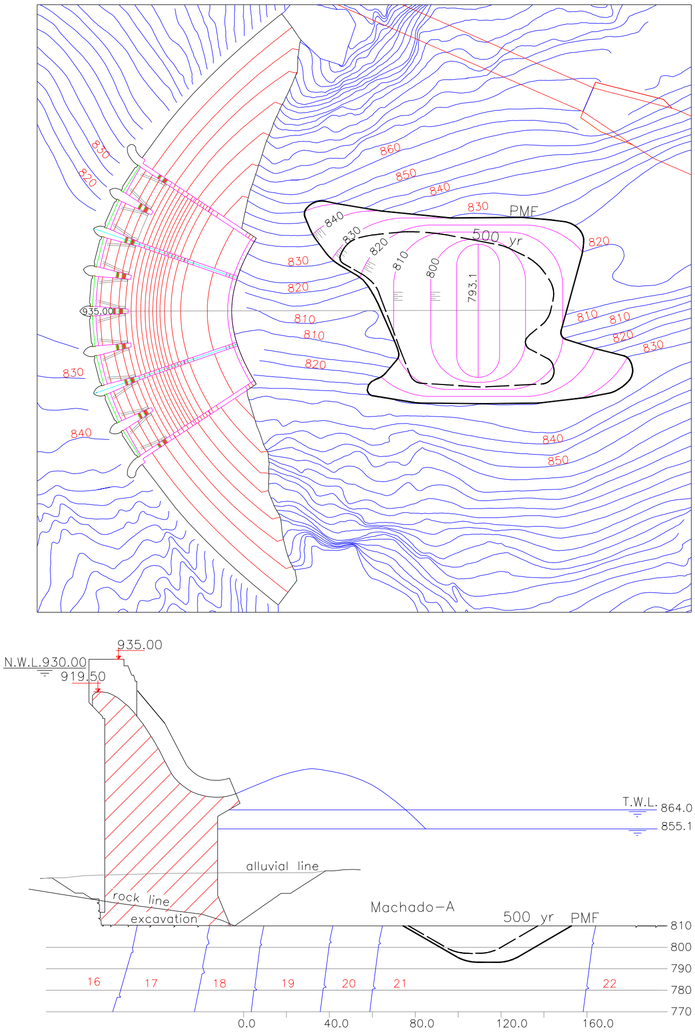

Figure 6. Maximum and probable scour extent, created by PMF and 500-years flood in Salman-Farsi Project, considering the time effect

6.2. *Recommendation*

To modify the results; the following remarks are recommended:

- Considering the primary and secondary rock characteristics such as RQD, joint spacing, uniaxial compressive strength, hardness and degree of weathering and using a scour model based on fully transient water pressures in rock joints according Bollaert (2002).

- Taking into account the high rate of scouring in the beginning stage of scour and the retard effect of tailwater depth to propose the scour rate as a combined by-linear-exponential function.
- Considering the effect of grouting of bed rock in the scour rate, regarding to the grouting at downstream of spillways in the most projects in Iran including Salman-Farsi Project.

Acknowledgement

Acknowledgements go to Mahab-Ghodss Consulting Engineers to have given me the opportunity to access the information of Salman-Farsi Project and their support.

Notations

a	: the site-specific constant
d_e	: '$(h+t)_e$' the maximum scour depth below tailwater level
d_s	: 'h + t' the scour depth below tailwater level, in terms of time
d_{90}, d_m, d_{50}	: grain size of bed rock
h	: tailwater depth at downstream of the spillway
H	: head of energy
q	: specific discharges ($m^3/s/m$)
q_{impact}	: specific discharges at the impact zone ($m^3/s/m$)
Q	: discharge (m^3/s)
R.W.L., T.W.L.	: Reservoir Water Elevation, Tail Water Elevation
T, T_e	: peak duration of the floods, the time at which equilibrium is attained

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