# EVALUATING THE TIME EFFECT ON SCOUR AND COMPARING THE DIFFERENT EXPERIMENTAL AND SEMI-EXPERIMENTAL FORMULAS

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In this article, 30 empirical and semi-empirical formulas have been compared to estimate the scour depth. Three formulas have been selected to predict a reasonable, a lower limit and an upper limit of scour depth. This study has been carried out particularly for characteristics of Salman-Farsi Dam, an arch gravity dam with a height of 132 m and 1400 million $m^3$ of reservoir volume, currently under construction in Iran. The influence of the grain size and the head loss on scour depth has been evaluated. The sensitivity of scour depth to the site-specific parameters has been investigated. Finally the scour depth downstream of Salman-Farsi Dam has been predicted by Machado-A formula considering the time effect.

## 1 Introduction

Since many years ago researchers have investigated the relation between the hydraulic characteristics of a falling jet and the formation of scour hole. The existing scour evaluation methods are:

- Empirical approaches based on laboratory and field observations.
- Semi-empirical methods combining laboratory and field observations.
- Approaches based on extreme values of fluctuating pressures at the plunge pool.
- Techniques based on time-mean and instantaneous pressure differences and accounting for rock characteristics.
- Scour model based on fully transient water pressures in rock joints (Bollaert 2002).

The scour depth estimated by different formulas occurs for a long duration of spillway operation, after the steady condition is achieved in the scour hole. The rate of scour is an exponential function of time and the site-specific parameters (Spurr 1985).

# 2 Scour formulas

A comparison of more than 30 empirical and semi-empirical formulas is carried out to estimate the maximum scour depth, as shown in Table 1. The scour formulas are classified in five groups. Group I express scour depth, '$d_s$', in terms of the head drop from upstream to downstream water level, 'H', the unit discharge of the jet at the point of impact, 'q', and, in some cases, the grain size of the bed materials, 'd'. The general form of the Group I formulas are:

$$d_s = k \frac{q^x H^y}{d^z}$$

In this group only the equation defined by Bisaz and Tschopp is slightly different:

$$d_s = kq^x H^y - k'd$$

in which k, x, y, z and k' are all constant for any given formula, as defined in Table 1.

This group has been subdivided in two subgroups; in the Subgroup GI-a there is no grain size effect. Group II formulas consider the tailwater depth h.

Group III formulas are simplified relations. Davis and Sorenson suggest a scour depth of two-thirds the height of fall. Cola, Hartung and Häusler consider a scour depth 20 times of the jet diameter and 40 times of the jet width (Whittaker & Schleiss 1984). This description seems simple but to define the diameter or width of jet is complicated; dependent to turbulent and jet characteristics. In the case study of Salman-Farsi Dam; definition of the jet width is more complex because of the curve shape of spillway and the special jet pattern. Thus, only Davis and Sorenson formula is applied in this group.

Group IV formulas comprise by Russian authors; are generally more complex than the others. Doddiah and Thomas, Group V, assume another type of concept by considering $W_m$ as the mean particle fall velocity.

The scour depth calculated by different formulas has been carried out for characteristics of Salman-Farsi Dam. The dam currently under construction is located on the Ghare-Aghaj River approximately 180 km South East of the city of Shiraz in Iran. 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. The rock mass of dam site is heterogeneous and the dam is founded on an Asmari limestone formation.The grain size for $d_{50}$, $d_m$ and $d_{90}$ are considered 0.25, 0.35 and 0.65 meter, respectively.

The scour depth is calculated for different floods, 2 years flood with q= 750 $m^3/s$, 1000 years flood with q= 8'618 $m^3/s$, 10'000 years flood with q= 13'476 $m^3/s$ and PMF with q= 19'303 $m^3/s$. For instance the comparative results of scour depth calculated by different forumlas for PMF are shown in Figure 1.

As it can be seen in Figure 1; the scour depth calculated by Machado-A formula, Group I-b, is at the middle range of all formulas and gives a reasonable amount for scour depth and near to some other formulas. Damle-C, Group I-a, and Jaeger, Group II, respectively, give one of the lower and upper limits of scour depth for Salman-Farsi Dam. These results are likely the same for the other floods.

Table 1. Scour formulas

| No. | Scour Formulas | $d_s = t + h$ (m) | Group |
|---|---|---|---|
| 1 | Veronese - B | $1.90\, q^{0.54} H^{0.225}$ | |
| 2 | Mod. Veronese | $1.90\, q^{0.54} H^{0.225} \sin\beta$ | |
| 3 | Damle - A | $0.652\, q^{0.50} H^{0.50}$ | |
| 4 | Damle - B | $0.543\, q^{0.50} H^{0.50}$ | |
| 5 | Damle - C | $0.362\, q^{0.50} H^{0.50}$ | |
| 6 | Martins - B | $1.50\, q^{0.60} H^{0.10}$ | G I – a |
| 7 | Taraimovich | $0.633\, q^{0.67} H^{0.25}$ | |
| 8 | Machado - B | $2.98\, q^{0.50} H^{0.25}$ | |
| 9 | Sofrelec | $2.30\, q^{0.60} H^{0.10}$ | |
| 10 | Incyth | $1.413\, q^{0.50} H^{0.25}$ | |
| 11 | Chian Min Wu | $1.18\, q^{0.51} H^{0.235}$ | |
| 12 | Fahlbusch | $1.849\, q^{0.50} H^{0.25}$ | |
| 13 | Schoklisch | $0.521\, q^{0.57} H^{0.2} / d_{90}^{0.32}$ | |
| 14 | Veronese - A | $0.202\, q^{0.54} H^{0.225} / d_m^{0.42}$ | |
| 15 | Hartung | $1.40\, q^{0.64} H^{0.36} / d_{85}^{0.32}$ | |
| 16 | Chee - Padiyar | $2.126\, q^{0.67} H^{0.18} / d_m^{0.063}$ | |
| 17 | Bisaz - Tschopp | $2.756 q^{0.5} H^{0.25} - 7.125\, d_{90}$ | G I - b |
| 18 | Chee - Kung | $1.663\, q^{0.60} H^{0.20} / d_m^{0.10}$ | |
| 19 | Machado - A | $1.35\, q^{0.50} H^{0.3145} / d_{90}^{0.0645}$ | |
| 20 | Kotoulas | $0.78\, q^{0.70} H^{0.35} / d_{90}^{0.40}$ | |
| 21 | Patrashew | $3.877\, q^{0.50} H^{0.25} / d_{90}^{0.25}$ *($d_{90}$, mm)* | |
| 22 | Jaeger | $0.6\, q^{0.50} H^{0.25} \left( h / d_m \right)^{0.333}$ | |
| 23 | Martins - A | $0.14 N - 0.73 h^2 / N + 1.7 h$, $N = 7\sqrt{q^3}\, H^{1.5} / d^2$ *($d_{90}$, mm)* | |
| 24 | Mpiri | $0.355\, (qz^2)^{0.5} (z_3 + h) / (g\, d_{50}^2 (z_3 + h)^3)^{0.25}$ | G II |
| 25 | Mason - A | $3.27\, q^{0.60} H^{0.05} h^{0.15} / ( g^{0.30} d_m^{0.10})$ | |
| 26 | Mason – B * | $K q^x H^y h^w / ( g^v d_m^z )$ | |
| 27 | Davis – Sorensen | $2/3\, H$ | G III |
| 28 | Mikhalev | $\{1.804\, q \sin\beta /(1-0.215 \cot\beta)\}\{(1/(d_{90}^{0.33} h^{0.5}))-1.126/H\}$ | G IV |
| 29 | Mirskhulava | $0.25h + \{(0.97/d_{90}^{0.5})-(1.35/H^{0.5})\}\{q \sin\beta /(1-0.175 \cot\beta)\}$ | |
| 30 | Thomas – Doddiah | $h + 2/3h\, (q/(H W_m))^{2/3} (H/h)^{2(q/(H W_m))1/6}$ | G V |

* $K = 6.42 - 3.10\, H^{0.1}$, $x = 0.60 - H / 300$, $y = 0.05 + H / 200$, $w = 0.15$, $v = 0.30$, $z = 0.10$
** In all above formulas, 'd', is in meter except Patrashew and Martin –A formulas

It is interesting that the positions of formulas change for different floods and different discharges. Some formulas whose positions in Figue 1 are in the middle, which give the middle range of scour depth, go towards the upper limits, while discharge decreases. Figure 2 shows this variation for some famous formulas in terms of discharges. As seen in Figure 2 the results of Machado-A and Damle-A are very close together for different discharges.

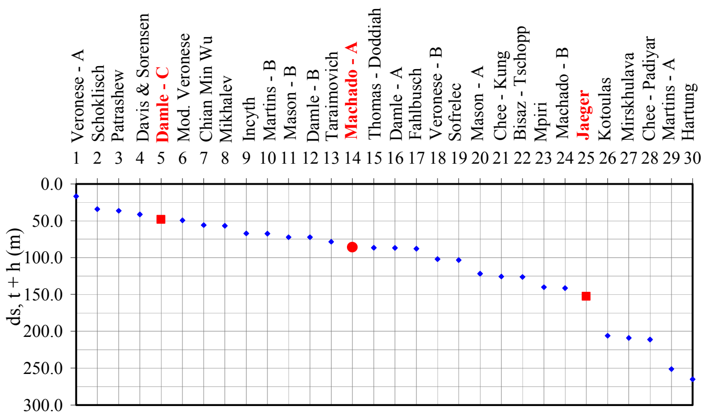


Figure 1. Ultimate scour depth $d_s$ ( t + h ) for PMF

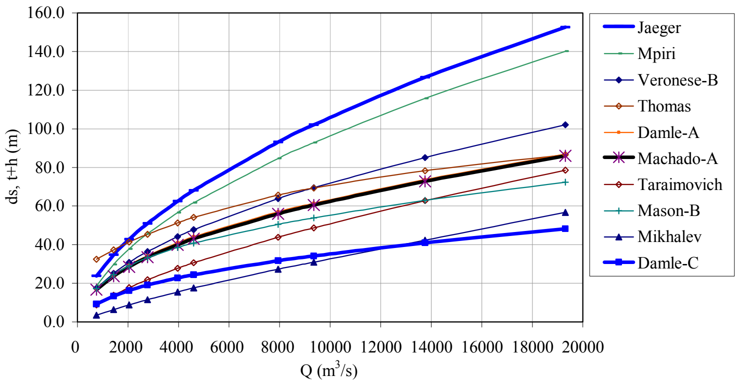


Figure 2. Sensitivity of scour depth $d_s$ ( t + h ) to discharge variation, calculated by different formulas

# 3 Sensitivity of scour depth to grain size and to head loss

### *3.1. Grain Size Sensitivity*

The Damle-C formula does not consider the effect of the grain size; Jaeger approach shows more sensitivity to the grain size than Machado-A approach. All of the formulas, described in Table 1, are more sensitive to the grain size less than 200 mm. The sensitivity of Machado-A formula is shown in Figure 3.

### *3.2. Head Loss Sensitivity*

The head loss sensitivity has been evaluated. The results are shown in Figure 4. In this graph $H_{effecive}$ shows the head considering the loss of energy through the spillway. In order to evaluate the sensitivity of scour depth to the loss of energy through the air; it has been considered the energy losses from 10 to 50 percentages of total head.

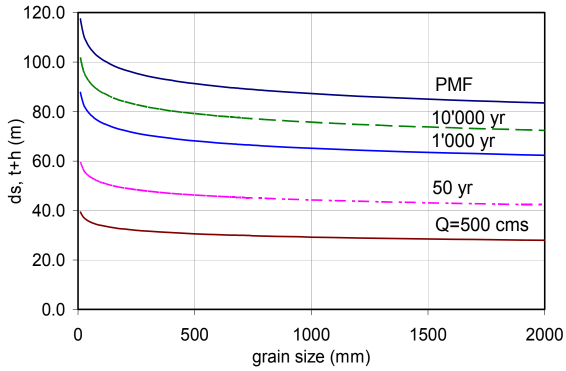


Figure 3. Sensitivity of Machado-A formula to the grain size

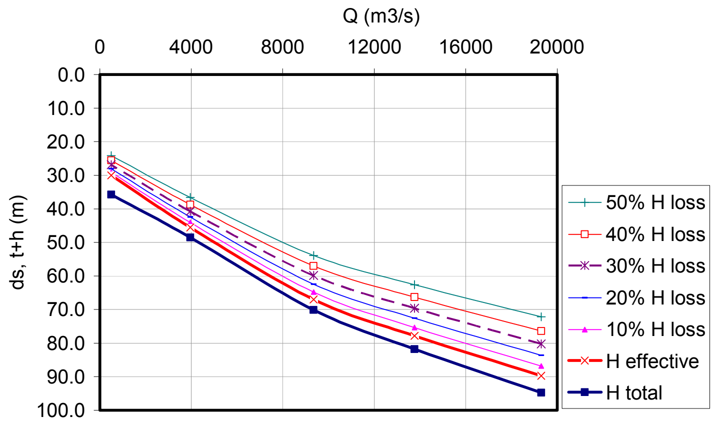


Figure 4. Sensitivity of Machado-A formula to the head loss

# 4 Time Effect

The ultimate scour depth, derived from different formulas occures 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). The main question is the definition of the site-specific constant. In order to answer this question; the results of the scour test of Gojeb Project, carried out by Greil (2003), have been utilized. These results present the three following points:

- More than 80 percent of scour happens in less than 10 percent of the ultimate time '$T_e$', and the initial part of the curve is almost linear with a high slop.

- The retard effect of tailwater depth on the scour rate creates a nearly horizontal part in the curve.
- These two phenomena do change the shape of the scour rate from an exponential curve to a curve combined of a linear part and an exponential part.

The exponential curve with ‘a=13’ shows the good adjustment to these results. The ‘T’ is defined by determining the peak time of different floods, from hydrographs of Salman-Farsi Dam. The scour rate is calculated by Machado-A formula and the results show:

- With increasing the scour equilibrium time, the curves with ‘a’ less than 13 give the underestimated scour depth especially for higher discharges.
- The exponential curves with ‘a’ more than 20 give the ratio of the scour depth to the maximum scour, ‘$d(T)/d_e$’, more than 80% for all ranges of equilibrium time and discharges.

For instance; the results of scour depth for different discharges and different values of ‘a’ and for ‘$T_e$=200’ are displayed in Figure 5.

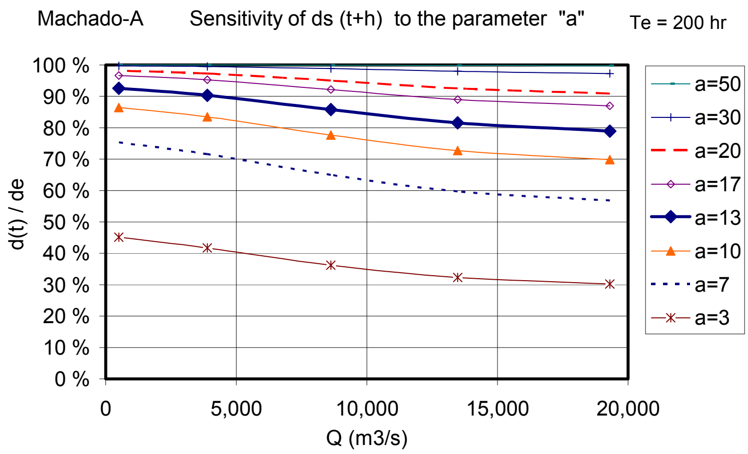


Figure 5. Sensitivity of scour depth to the site-specific constant ‘a’

Figure 6 represents the proposed scour rate based on the above results.

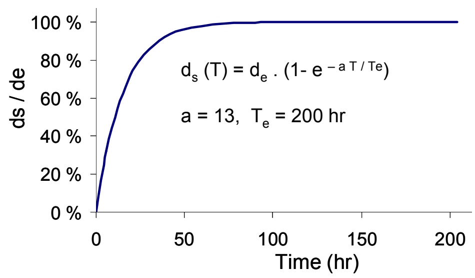


Figure 6. Proposed scour rate

# 5 Results

By considering the time effect and comparing the different scour formulas, the scour depth for Salman-Farsi project has been calculated. The Machado-A formula is selected to define the scour depth and the Kawakami approach is used to predict the trajectory length. The predicted scour depth is presented in Table 2.

It should be mentioned that because of the curved shape of the spillway to determine the scour depth and the $q_{impact}$ it was needed to know the jet pattern, which is the results of another research of the authors of this paper.

Table 2. 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

# 6 Conclusion and Recommendation

## 6.1. *Conclusion*

Comparing 30 scour relations shows that Machado-A approach gives the middle range of the scour depth predicted by all the formulas. The Damle-C and Jaeger are selected, respectively, as the lower and upper limits to determine the scour depth. The grain size and the head loss sensitivity were evaluated.

The time effect on scour depth was investigated. The site-specific constant 'a' was predicted on the basis of the scour test of the Gojeb project, carried out by Greil (2003), and then the time effect was evaluated. These results show the retard effect of tailwater depth and the high rate of the scour during the time less than 10% of the equilibrium time. Furthermore, the sensitivity of the scour depth to the site-specific constant 'a' and to the equilibrium time 'Te' was investigated for the Salman-Farsi Project.

Based on the results, the scour depth of downstream of Salman-Farsi dam was predicted by Machado-A formula considering T=200 hours and a=13 for different floods.

## 6.2. *Recommendation*

To modify the results; the following remarks are recommended:

- 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

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### 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 considering the time effect |
| $d_{90}$, $d_m$, $d_{50}$ | : 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 | : peak duration of the floods |
| $T_e$ | : the time at which equilibrium is attained |

### References

Bollaert, E. 2002, Transient Water Pressures in Joints and Formation of Rock Scour due to High Velocity Jet Impact, Communication No. 13, LCH, Lausanne, EPFL.

Greil, A. 2003, Diplomarbeit – Parameter für die Kolkentwicklung bei einem Skisprung. Vergleichende Untersuchungen, , VAW – ETH, Zürich.

Mason, P. J. & Arumugam, K. 1985. Free jet scour below dams and flip buckets, *Journal of Hydraulic Engineering, ASCE*, vol. 111.

Schleiss, A., 2002. Scour evaluation in space and time- the challenge of dam designers, *International Workshop on Rock Scour*, Lausanne, EPFL.

Spurr, K. J. W. 1985. Energy approach to estimating scour downstream of a large dam, *Water Power and Dam construction.*

Technical Report of Salman Farsi ( Ghir ) Dam Project, Mahab-Ghodss, Tehran,1994 (In Farsi).

Whittaker, J., Schleiss, A., 1984, Scour Related to Energy Dissipaters for High Head Structure, Zürich.