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Optimization of the Sefid-Roud Dam desiltation process using a sophisticated one-dimensional numerical model

Ali KHOSRONEJAD[1]

Abstract

Although water and soil conservation activities reduce reservoir sedimentation, it is inevitable that reservoirs fed by rivers transporting high amounts of sediment will experience sedimentation. The Ghezel-Ozan and Shah-Roud rivers, which flow to the Sefid-Roud reservoir dam, are both highly sediment-laden and transport significant amounts of sediment in both bed load and suspended load forms to the reservoir. Hence, it seems that the only practical way to remove the sediment from the reservoir is to flush it out using the Chasse method. In the present paper, field measurements of Chasse operation characteristics taken in previous years are presented, and a numerical model that simulates this process is introduced. After calibrating the model using field measured data, the calculated results (for reservoir pressure flushing and released sediment volume) of the numerical model were compared with other measured data for the same Chasse operation and the results agree well. Finally, using the numerical simulation results, the best approaches to ensure highly effective flushing while conserving reservoir water are presented (at least for the Sefid-Roud dam). The operation of the bottom outlet gates, the shape of the output hydrograph, and the reservoir water level variation during flushing were optimized. In addition, the numerical model and related parameters, which need to be calibrated, are discussed.

Key Words: Pressure flushing, Numerical model, Reservoir water level, Bottom outlet, Chasse operation

1 Introduction

The Sefid-Roud dam was commissioned in 1963, is located in northern Iran, 250 km northwest of Tehran (Fig. 1), and its main purpose is irrigation. It is a buttress gravity dam with a watershed area of 56,200 km^2, height of 106 m, crest width of 425 m, storage capacity of 1.76 billion m^3 at normal water level, ratio of storage capacity to inflow water of 0.36 and power generation capacity of 87.5 MW. The average long-term annual inflow sediment load (based on hydrographs) and inflow water volume are 48 million tons and 4,835 million m^3, respectively. Without sediment venting activities (including flushing, dredging and density current venting) and through a normal operation period, the sediment outflow from the reservoir is 14 million tons per year. Therefore, with no sediment venting measures, there is a significant storage capacity loss of 2.3% per year owing to sedimentation (Tolouei et al., 1993).

The evacuation facilities of the Sefid-Roud dam include two morning glory spillways, two auxiliary spillways, five power intakes and five bottom outlets with discharge capacities of 3,000, 2,000, 160, and 980 m^3/s, respectively, giving a total discharge capacity of 6,140 m^3/s (at maximum water level). Figure 2 shows the detailed cross section view of evacuation systems of the Sefid-Roud Dam. Figure 3 shows the bottom outlet sizes, locations and elevations on a cross section of the Sefid-Roud Dam at a distance of 0.0 m from the dam body.

[1] Assis. Prof. of the Water Eng. Dept., University of Guilan., Rasht, Iran, E-mail: ali_khosro2001@yahoo.com, and Post Doctoral Associate, St. Anthony Falls Laboratory, University of Minnesota, Minneapolis, Minnesota 55414

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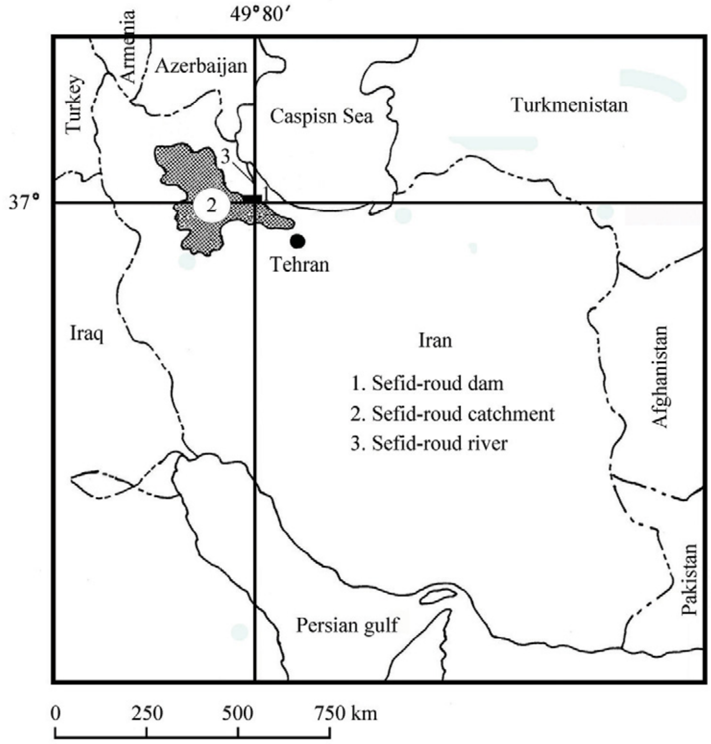

Fig. 1 Location of the Sefid-Roud dam and its watershed

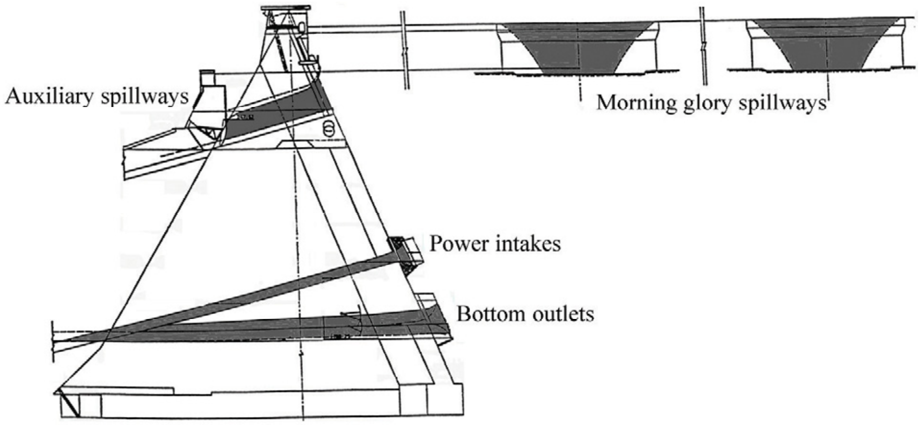

Fig. 2 Cross section view of the evacuation system of the Sefid-Roud dam

Because of problems caused by reservoir sedimentation, many researchers have carried out different investigations to remove or reduce the negative effects of sediment deposition in reservoirs, which reduces worldwide reservoir volume by almost 1% annually (Fan and Morris, 1992). Based on the results of multiple investigations on this issue, one or more of the following methods can be used effectively to resolve the problem.

a) Reservoir desiltation by flushing (Chasse) technique. The bottom outlets are opened so that an amount of water is released and sediment is removed from the reservoir via high turbulent flow in the reservoir.

There are two types of flushing. The first is free-flow flushing in which the reservoir is emptied and inflowing water from upstream is routed through the reservoir to the downstream river (Morris and Fan, 1998). The water level is lowered very quickly and thus a large volume of water is lost.

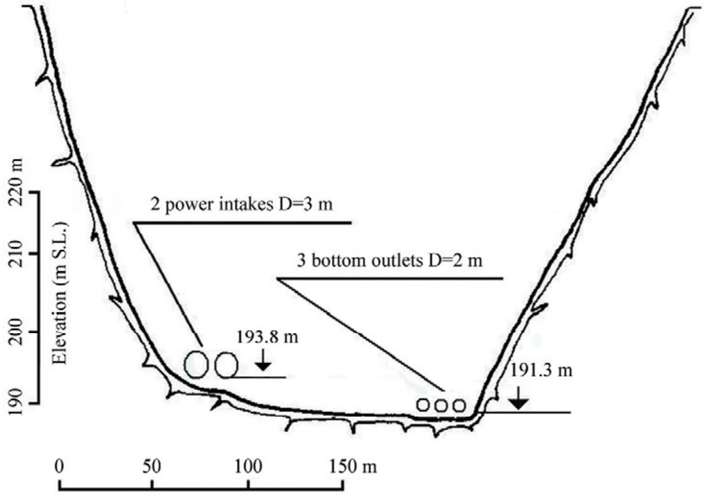

Fig. 3 Cross section view of the bottom outlet system of the Sefid-Roud dam

The other flushing method is pressure flushing in which only a limited area of the reservoir is affected (Fig. 4). During pressure flushing the reservoir water is kept at a higher level than the outlet levels and there is flow from the bottom outlets due to pressure. Sediments are scoured and vented in the areas closer to outlets in a relatively short period of time and a wedge-shaped flushing cone forms in front of the bottom outlets. Eventually, generally several hours after the operation begins, the shape of the flushing cone reaches equilibrium and no more sediment venting occurs. The total volume of sediment evacuated by pressure flushing, in comparison to that evacuated by free-flow flushing, is relatively small.

Usually flushing is performed in seasons during which there is little demand for water. For instance, this method is used to flush out the Sefid-Roud dam reservoir annually, in September and December. Practice has shown that it takes several days for the sediment from remote areas of the reservoir to entrain and reach the dam body and flush out through the bottom gates. Therefore, it is crucial to preserve water, so that there is sufficient volume to flush sediment that has reached the dam from remote areas.

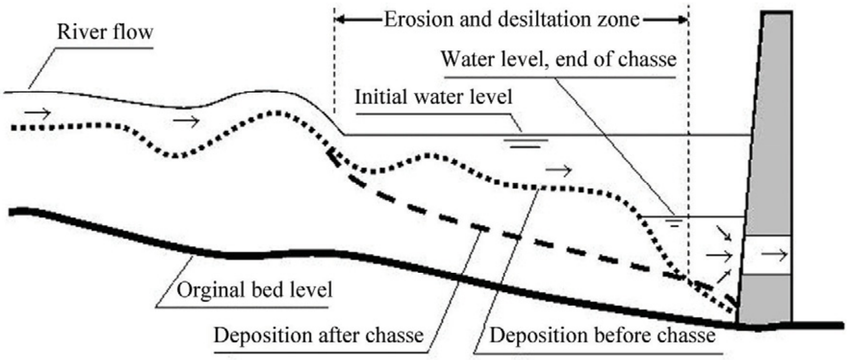

Fig. 4 Schematic view of reservoir flushing using the pressure flushing method

b) Reservoir desiltation through flood flow. Because most of the sediment volume enters the reservoirs with floods, most of reservoir sediment could be flushed out by flood flows if the flow through the bottom outlets is of the same order as the flood flow. In addition, because of the highly turbulent flow of a flood, a large volume of deposited material could also be entrained and discharged with this flow through the bottom gates. In some reported cases in China, up to 100% of inflow sediment has been removed using this method (Fan and Jang, 1980).

c) Density current flushing. As mentioned above, flood flows contain large amounts of suspended sediment, and in some conditions the high concentration inflows could constitute a layer of dense current at the bottom of the reservoir moving toward the dam body parallel to the bed. The highly-concentrated flow of the solid mass near and parallel to the bed moving downstream is called a density current. In extreme cases these flows cause most of the reservoir sedimentation. If the arrival time, movement speed, flow width and depth of the density current can be well-predicted, the sediment may be flushed out successfully and thus a large reservoir volume can be maintained in a safe and cost-effective manner (Fan, 1995). The density current velocity depends on the velocity of the flood flow, and if the bottom outlets have sufficient capacity and are positioned at a suitable level on the dam body, they can pass a significant amount of the density current. Up to 70% flushing of the density current was reported by Fan (1995).

Using one or more of these methods, a successful flushing operation can be achieved to prolong the useful life of a dam reservoir. However, it should be noted that there are some crucial restrictions that need to be considered.

a) The environmental impacts of all methods should be investigated;

b) The high sediment concentration in outlets may cause damage by creating cavities;

c) The sliding of sediment near the outlets may plug gates and therefore proper soil mechanics tests on the sediment near outlets should be done to evaluate its sensitivity to sliding.

From 1963 to 1980, during the first 17 years of operation, no sediment venting activities were conducted for the Sefid-Roud dam. When venting was first conducted in 1980 and 1981, sediment venting using the pressure flushing method was carried out, and afterward free-flow flushing operations were conducted until recently. The quantity of water and sediment outflow from Sefid-Roud dam during the operation period of 1963 to 1990 is illustrated in Fig. 5. As shown in the figure, the average annual sediment outflow for non-flushing years (1963 to 1980) and flushing years (1980 to 1990) are 14 and 44 million tons, respectively.

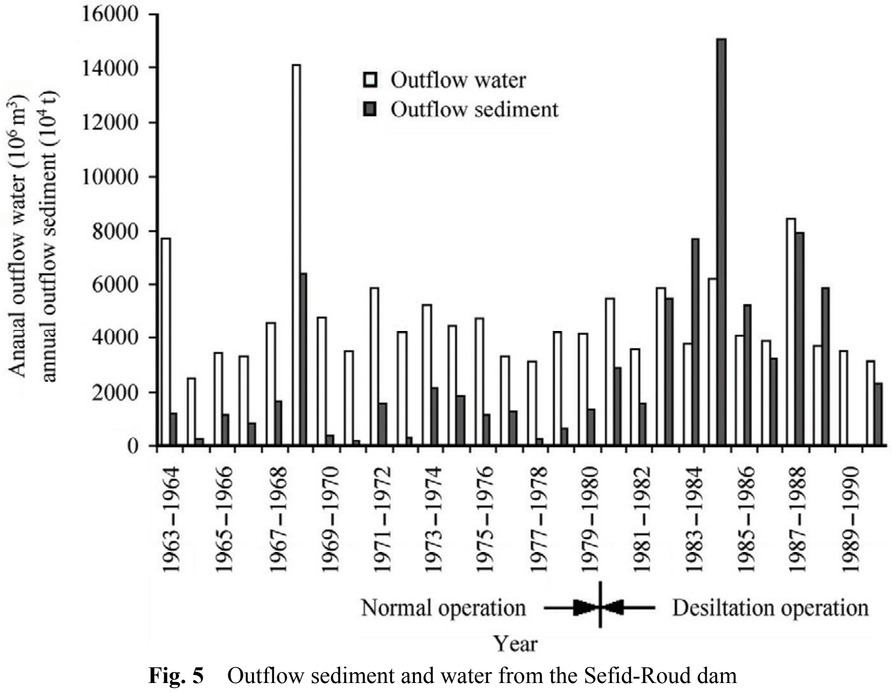

Fig. 5 Outflow sediment and water from the Sefid-Roud dam

The sediment outflows were 24 and 12 million tons for the flushing years of 1980 and 1981, respectively, and 52, 68, 142, 46 and 27 million tons for the non-flushing years from 1981 to 1990 (Tolouei, 1993).

The sediment trapping efficiency of the reservoir during normal operation years and the first three flushing years was 79 and 37%, respectively. However, since 1992, the sediment outflow with flushing exceeded the sediment inflow and the reservoir volume became roughly constant (Fig. 6).

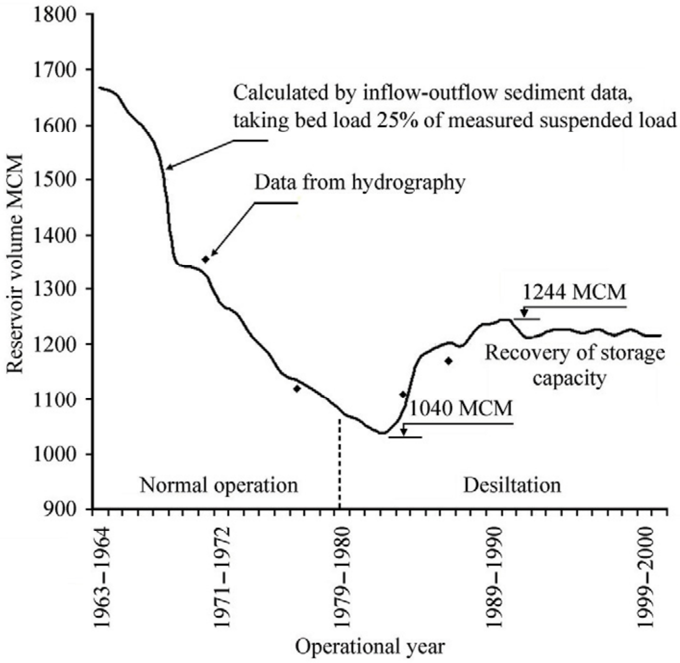

Fig. 6 Trend of restoring the Sefid-Roud dam reservoir volume (Tolouei et al., 1993)

In the following, a numerical model has been adopted to model the pressure flushing of the Sefid-Roud dam. One of the most important tasks in the numerical modeling is calibrating the model based on previous data from the same reservoir. In this study, the field measured data of Sefid-Roud pressure flushing in 1981 and 1980 have been used to calibrate and verify the present model, respectively.

2 Governing equations of the numerical model

2.1 Hydrodynamic model

The unsteady flow field far from the dam body in the reservoir is simulated using the following one-dimensional equations (Graf, 1998).

Momentum equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial (QV)}{\partial x}+\frac{g}{\gamma}\frac{\partial Z}{\partial x}A+\frac{g}{\gamma}\frac{V^2 n^2}{R^{4/3}}A=0 \tag{1}$$

where Q is the flow discharge, V is the mean velocity of each vertical section, t is time, x is the longitudinal coordinate axis, g is gravitational acceleration, Z is the water surface elevation, n is the Manning friction coefficient, γ is the fluid specific gravity, A is the flow cross section area, and R is the channel hydraulic radius.

Continuity equation:

$$\frac{\partial Z}{\partial t}+\frac{1}{B}\frac{\partial Q}{\partial x}=0 \tag{2}$$

where B is the flow width at the free surface.

Near the dam body, where a high shear layer exists and the flow field is similar to a free jet flow, the velocity profile of the flow can be estimated as (Chatterjee and Ghosh, 1980)

$$U(\hat{x},\hat{y})=U_{Max}.e^{(0.5(\hat{y}/C_v\hat{x})^2)} \tag{3}$$

where $\hat{x},\hat{y}$ are local coordinates in the jet equation, U_{Max} is the maximum velocity in a vertical section of the free jet near the dam body (given by Eq. (4)), and C_v is the velocity coefficient, which is 0.81 (a measured value for the Sefid-Roud dam bottom outlets).

$$U_{Max} = 6.2 C_C \frac{D}{x_D} (2gH)^{0.5} \tag{4}$$

where x_D is the longitudinal distance from the dam body, H is the water column height above the bottom outlet, D is the bottom outlet diameter, and C_C is the contraction coefficient of the bottom outlet, which is between 0.7 and 0.9 and for this study 0.87 was used for the Sefid-Roud bottom outlets (Mahab Ghodss Co. report, 1997).

The equation used to compute the mean velocity at a distance x_D from the dam body is

$$V = \frac{1}{A} \int_A U(\hat{x}, \hat{y}) dA \tag{5}$$

The flow field close to the bottom outlets is simulated two-dimensionally by considering Eqs. (3), (4) and (5). In areas of the reservoir far from the outlets, Eqs. (1) and (2) are used to calculate the reservoir water level and one-dimensional flow velocity V.

2.2 Sediment transport model

Once the flow field is solved, the flow field results will be used to solve the sediment transport equations. The sediment transport equations include the advection–dispersion equation of sediment concentration and sediment continuity (Exner) equations.

In the sediment transport model, the sediment concentration must first be calculated using the following advection–dispersion equation (Yalin, 1977).

$$\frac{\partial C}{\partial t} + \frac{\partial (VC)}{\partial x} = \frac{\partial}{\partial x}\left(\upsilon_t \frac{\partial C}{\partial x}\right) + S_c \tag{6}$$

where C is the sediment concentration, υ_t is the eddy viscosity (turbulent dispersion coefficient), which includes the molecular dispersion coefficient, and S_c is the source term that shows the effects of sediment particle deposition and entrainment. The effect of turbulence dispersion is taken into account in the modeling through the υ_t term.

The source term S_c is calculated by

$$S_c = \Psi \frac{\partial C_T}{\partial t} \tag{7}$$

where C_T is the transport capacity of the flow field, which is dependent on the flow velocity and sediment concentration in the flow (Kerssens et al., 1979), and Ψ is a coefficient that depends on the sign of $\partial C_T / \partial t$. The England–Hansen equation is applied to compute the sediment transport capacity (Engelund and Hansen, 1967; Yang, 1996):

$$C_T = 0.05 \left[\frac{s}{s-1}\right] \cdot \left[\frac{V.S_f}{\sqrt{(s-1)g.d_m}}\right] \cdot \sqrt{\frac{R.S_f}{(s-1)d_m}} \tag{8}$$

where s is the sediment specific gravity, S_f is the channel energy slope, and d_m is the median grain size. Once the advection–dispersion equation of the sediment concentration is solved, the obtained sediment concentration will be applied to solve the sediment continuity equation. The sediment continuity equation, in one-dimensional form, is (Chen, 1971)

$$\frac{\partial A}{\partial t} + \frac{\partial (CA)}{\partial t} + \frac{\partial (CQ)}{\partial x} = 0 \tag{9}$$

This sediment continuity equation is used to compute the reservoir cross section changes due to flushing.

3 Numerical algorithm

To solve Eqs. (1) to (9), the explicit finite difference method is adopted. Because an explicit method could lead to an instability, a time step limiter is used to ensure the stability of the adopted numerical method. The stability condition is based on a Fourier series (Chen, 1971). The reliable time step to satisfy the stability condition was found to be less than 1.0 hours and thus a time step of 30 minutes was used to ensure stability.

To present the numerical schemes used for Q, V, C, and A, a new function $f(x,t)$ is assumed to represent different variables.

Time derivations in Eqs. (1) and (6) are descretized:

$$\frac{\partial f_i^n}{\partial t} = \frac{(f_i^{n+1} - (\varphi f_i^n + (1-\varphi)(f_{i+1}^n + f_{i-1}^n))}{\varphi.\Delta t} \tag{10}$$

where f_i^n is the variable at time n and location i, f_i^{n+1} is the variable at time $n+1$ and the same location, f_{i+1}^n and f_{i-1}^n are variables at time n and locations $i+1$ and $i-1$, respectively, Δt is the time step, and φ is a time-weighted coefficient. The time derivatives in Eqs. (2) and (9) are descretized, without using the time-weighting coefficient:

$$\frac{\partial f_i^n}{\partial t} = \frac{f_i^{n+1} - f_i^n}{\Delta t} \tag{11}$$

In addition, spatial derivatives in equations (1) and (6) are

$$\frac{\partial f_i^n}{\partial x} = \theta.\frac{f_{i+1}^n - f_i^n}{\Delta x} + (1-\theta).\frac{f_i^n - f_{i-1}^n}{\Delta x} \tag{12}$$

where Δx is the spatial step along the longitudinal coordinate axis, x, and θ is a spatially weighted coefficient.

The spatial derivatives in Eqs. (2) and (9) are

$$\frac{\partial f_i^n}{\partial x} = \left[\frac{\theta}{2}\right].\frac{f_{i+1}^{n+1} + f_{i+1}^n - f_i^{n+1} - f_i^n}{\Delta x} + \left[\frac{1-\theta}{2}\right].\frac{f_i^{n+1} + f_i^n - f_{i-1}^{n+1} - f_{i-1}^n}{\Delta x} \tag{13}$$

The governing equations were descretized using Eqs. 10 to 13, and solved by the following sequence. First, Eqs. 3, 4 and 5 were solved to determine the flow velocity in the area near outlets, and then Eqs. 1 and 2 were solved to find the one-dimensional flow velocity throughout the reservoir. Having computed the flow hydrodynamics, the advection–dispersion equation of sediment concentration (Eq. (6)) was solved to calculate the sediment concentration across the reservoir. By solving Eq. (9) (the Exner or sediment continuity equation) and using computed flow hydrodynamics and sediment concentration, the bed evolution of the reservoir during pressure flushing was numerically computed.

4 Model calibration

To calibrate the numerical model, field measured data of the sediment concentration downstream of the dam were used. Borings through the reservoir at different locations show the average composition of deposits is 41% sand and 59% clayed silt. The reservoir sediment density, on average, is 1.20 tons/m^3 for clayed silt regions and 1.45 tons/m^3 for sand regions, giving an average sediment density for the reservoir of 1.3 tons/m^3.

The measured reservoir water levels during flushing in 1980 and 1981 are shown in Figs. 7 and 8. The bottom outlet invert elevation is 193.8 m and, as shown in these figures, the water level is always higher than this height, which shows the nature of pressure flushing.

The outflow discharges from the bottom outlets have also been measured and are used as the boundary condition for outflow. Figures 9 and 10 show the measured outflow discharge, which is the value applied as the boundary condition for outflow from the bottom outlet in the modeling of the flow field.

In the process of calibration, the parameter Ψ is tuned so that the computed output sediment concentration tends to the measured values as much as possible. For this purpose, field measurements of sediment concentration with Chasse operation in 1981 taken at the downstream station of Roudbar have been used. In the calibrating process, the numerical model is run 30 times and each time the computed and measured results are compared to tune the parameter Ψ. Figure 11 shows the computed and measured results at the beginning of calibration. As shown in this figure, the model results are not acceptable and there is large discrepancy.

At the end of the calibration, the model is sufficiently tuned to produce results that are in good agreement with the measurements. Figure 12 shows the computed and measured concentrations at the end of the calibration. As seen in Fig. 12, the calibrated model can predict the output sediment concentration during the flushing operation sufficiently well and the discrepancies are insignificant. By multiplying the sediment concentration with the outflow discharge at the related time, one can compute the sediment load released from the reservoir by flushing.

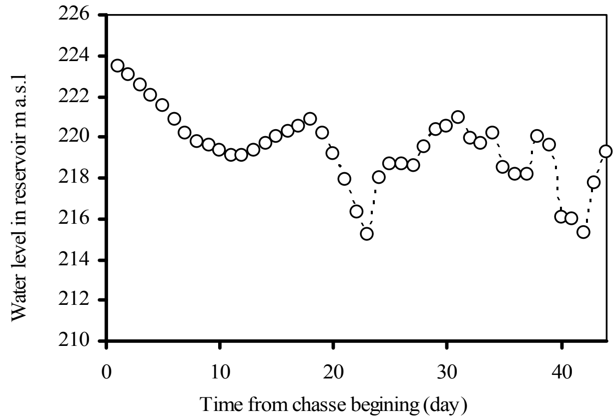

Fig. 7 Reservoir water level (measured) during flushing in 1980 (day zero is Sept. 23rd)

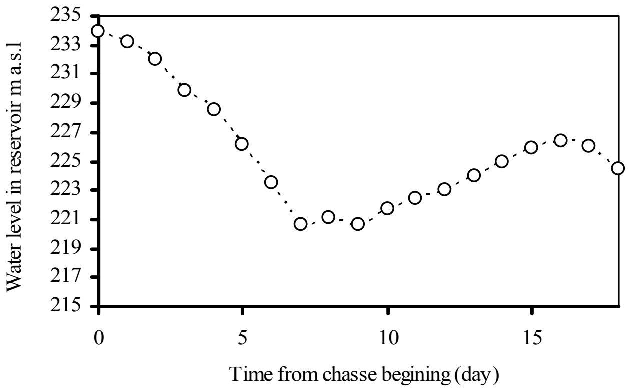

Fig. 8 Reservoir water level (measured) during flushing in 1981 (day zero represents Sept. 27th)

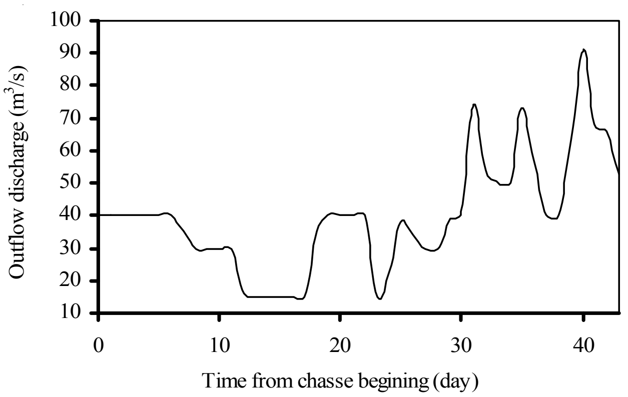

Fig. 9 Reservoir outflow discharge (measured) during flushing in 1980 (day zero represents Sept. 23rd)

However, the main purpose of a model is to predict a phenomenon that it has not experienced before. To challenge the model, in the next section, it is run for the Chasse operation of the Sefid-Roud reservoir in 1980.

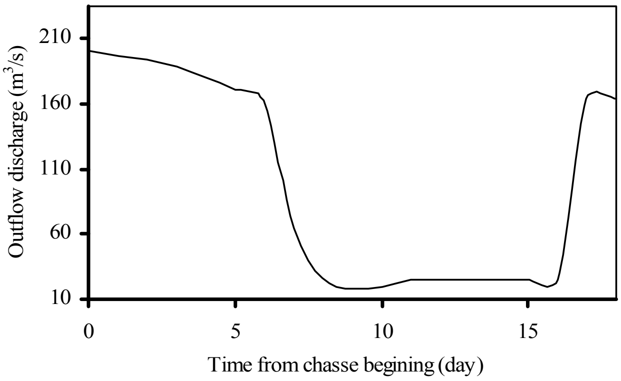

Fig. 10 Reservoir outflow discharge (measured) during flushing in 1981 (day zero represents Sept. 27th)

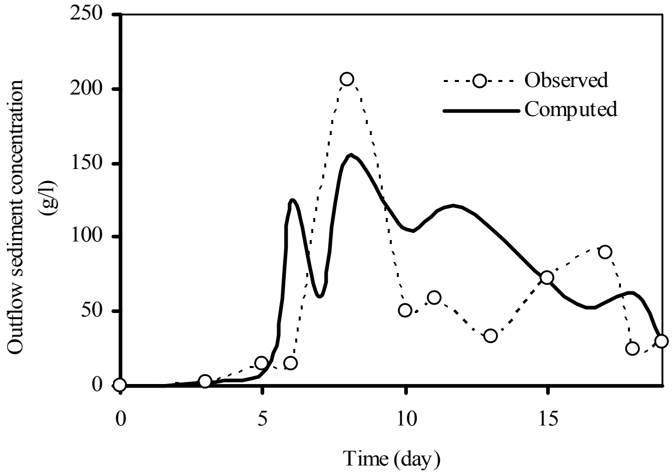

Fig. 11 Computed and measured output sediment concentrations at the beginning of the calibration process (before calibration) for the Chasse operation in 1981 (day zero is Sept. 27th)

5 Model verification and application

The pressure-flushing operation of the Sefid-Roud reservoir in 1980 was chosen to verify the model results. Note that the model has not experienced the data of flushing in 1980 in the calibration process. The outflow sediment concentration during this Chasse operation was measured at the Roudbar station. The model is run for the same conditions as for the Chasse operation in 1980; e.g., the outlet gate dimensions and sediment particles are the same. The computed and measured results of this flushing operation are shown in Fig. 13. The results show that after calibration, the numerical model can estimate the phenomenon fairly well. Figure 14 shows the computed outflow concentration versus measured values. The mean computational error is 32.1% (for measured and computed results of Fig. 13), which is fairy acceptable for such simulations.

However, there are some discrepancies between the computed and measured results that could be due to the following.

a) The deposited sediments may consolidate during a given year, and this can affect the calibrating parameter. The consolidation effect must be considered in future studies.

b) The present model is one-dimensional while the phenomenon we are dealing with is essentially three-dimensional.

After the model was calibrated and verified, it was applied to different scenarios of Sefid-Roud reservoir flushing. In these scenarios, different output hydrographs, bottom gate maneuver strategies, and water surface levels were selected. As a result, the most effective way in which the maximum volume of sediment is flushed out with the minimum volume of water was deduced (given in the conclusion).

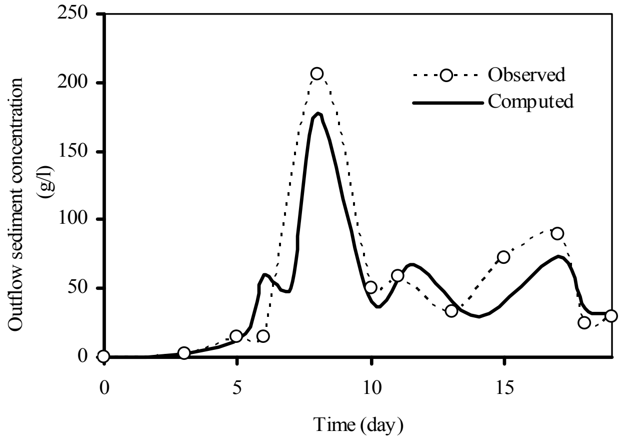

Fig. 12 Computed and measured output sediment concentration at the end of the calibration process (after calibration) for the Chasse operation in 1981 (day zero is Sept. 27th)

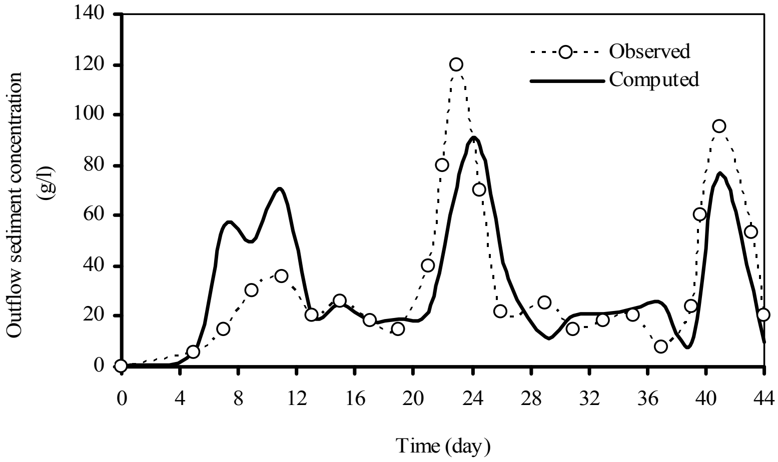

Fig. 13 Computed and measured output sediment concentration results for the Chasse operation in 1980, which has not been experienced by the model (day zero is Sept. 23rd)

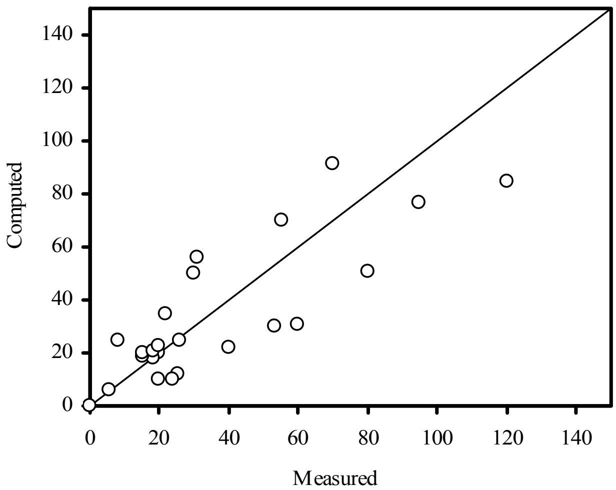

Fig. 14 Measured sediment concentration versus related computed value for flushing in 1980, which has not been experienced by the model previously

6 Conclusions

In this study, a numerical model was adopted to predict the pressure flushing process of the Sefid-Roud reservoir. The numerical model's mean computational error was 32.1%. After tuning, the model was used to produce practical guidelines for optimized flushing, in which the maximum volume of sediments is evacuated with the minimum volume of water. Therefore, the model is applied to different flushing scenarios and the following results, in brief, were obtained.

a) The results of numerical modeling show that when the water surface is at its lowest level (210 m or less), the sediment concentration at the outlet is a maximum.

b) The highest sediment concentration at the outlets is about 30 g/L.

c) To ensure the most effective pressure flushing, at the beginning of operation the outlet discharge should be high (about 300 m^3/s to 500 m^3/s) and to conserve the volume of water the gates should be opened and closed periodically. After the sediment concentration reaches a maximum, the discharge should be reduced to save water.

d) Once the sediment concentration reaches a maximum, the outlet discharge has no significant effect on the sediment concentration at the outlet. Therefore, to conserve the water of the reservoir, the discharge can be kept at a lower level (say 100 to 150 m^3/s).

e) The river flow has no significant effect on pressure-flushing efficiency.

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Notations

A = flow cross section area;

B = flow width at the free surface;

C = sediment concentration;

C_C = contraction coefficient of bottom outlet;

C_v = velocity coefficient;

C_T = sediment transport capacity of flow field;

D = bottom outlet diameter;

d_m = median grain size;

$f(x,t)$ = function representing dependent variables;

f_i^n = function $f(x,t)$ at time n and location i;

f_i^{n+1} = function $f(x,t)$ at time $n+1$ and location i;

f_{i+1}^{n} = function $f(x,t)$ at time n and location $i+1$;
f_{i-1}^{n} = function $f(x,t)$ at time n and location $i-1$;
g = gravitational acceleration;
H = water column height above the bottom outlet;
n = Manning friction coefficient;
Q = flow discharge;
R = channel hydraulic radius;
s = specific gravity of sediment material;
S_f = energy gradient;
S_c = source term of the sediment concentration in the advection–dispersion equation;
t = time;
U_{Max} = maximum velocity in a vertical section of a free jet;
V = flow velocity;
x = longitudinal coordinate axis;
x_D = longitudinal distance from dam;
$\hat{x}, \hat{y}$ = local coordinates in free jet equation;
Z = water surface elevation;
Δx = spatial step in the x direction;
Δt = time step;
γ = fluid specific gravity;
υ_t = eddy viscosity;
Ψ = constant coefficient;
φ = time weighted coefficient;
θ = space weighted coefficient.