INTERNATIONAL SYMPOSIUM ON
DAMS FOR A CHANGING WORLD
-Need for Knowledge Transfer across the Generations & the World
Kyoto, Japan June 5, 2012

Three-Dimensional Numerical Study of the Flushing Process in a Dam Reservoir

A.R. Mansoori
Graduate School of Engineering, Kyoto University, Japan
mansoori@uh31.dpri.kyoto-u.ac.jp

H. Nakagawa
Disaster Prevention Research Institute, Kyoto University, Japan

The numerical simulation of flushing in the reservoir of a dam plays a major role in the design, performance and management of the dam's system. To preserve the storage capacity of the reservoir, flushing is the only economic strategy to restore the live-storage of the reservoir rapidly. It has been proven that pressure flushing in dams is quite a 3-D phenomenon. Using horizontal 2-D modelling for this kind of phenomenon cannot give reliable results, as the main assumption of such models relies on the vertical profiles of velocity and sediment concentration being uniform along the depth, which is not the case during the operation of pressure flushing. In this study, a 3-D numerical model has been applied in a simplified dam reservoir to facilitate greater understanding and management during the flushing process of the reservoir in different modelling scenarios. The results, including the changes in bed topography near the outlets after the flushing as well as the volume of the emptied sediment, have been discussed in detail.

Keywords: Pressure flushing, Reservoir, Draw down, SSIIM, CFD

About 1% of the total storage capacity of the world's reservoirs is lost annually due to sedimentation (Mahmood, 1987 and Yoon, 1992). This amount is equal to replacing approximately 300 large dams annually worldwide, at an estimated cost of $9 billion to replace existing storage capacity (Annandale, 2001). Furthermore, the rapid reservoir sedimentation not only decreases the storage capacity, but also increases the probability of flood inundation in the upstream reaches, due to heightening of the bed elevations at the upstream end of the reservoir and the confluences of the tributaries (Liu et al., 2004).

To maintain the storage capacity of the reservoir, appropriate methods for controlling sedimentation in each reservoir are necessary (Un, 2006). Reviews of different control methods for reservoir sedimentation have been presented by Brown (1943), Fan (1985a, 1985b), and Brabben (1988). Morris and Fan (1997) classified the strategies to control reservoir sedimentation as three main categories: (1) reduction of sediment yield; (2) sediment excavation; and (3) hydraulic regime methods, such as sediment routing and flushing. Although these sediment control measures are usually adopted in combinations for maximum effect, among these approaches (Liu, et al. 2004), flushing is considered the only economic approach to swiftly restore the storage capacity of a reservoir with severe deposition (Kantoush et al., 2010). The flushing process can be defined basically as the opening of the outlet(s) to erode accumulated sediments. Nevertheless, the effectiveness and the process of flushing depend on the depositional pattern of the sediment (Jugović et al., 2009). Figure 1 shows the two main typical patterns of the longitudinal deposit in the reservoirs of the dams.

In high-sediment-laden flows, sediment may reach the downstream end of the reservoir quickly, resulting in a wedge-shaped deposition with its apex very close to the dam. A wedge-shaped deposition can also form if the water level is allowed to be drawn down regularly. In addition, deltaic deposits may migrate toward the dam causing the entire reservoir depositional pattern to become wedge-shaped. Thus, the wedge-shaped depositional pattern could be the equilibrium state for any reservoir in the long run (Lai, 1994).

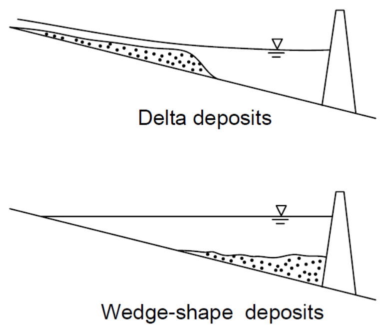

Figure 1. Schematic sketch of the typical patterns of the longitudinal deposits in the reservoirs (Un, 2006)

1.1. Classification of the Flushing

Based on the level of the water in the reservoir and the maximum level of the outlet, flushing can be classified as either pressure flushing or free flushing. During pressure flushing, the water releases through the bottom outlets while the water level in the reservoir is kept higher than the top level of the outlets. During free flushing, the reservoir has been emptied and the inflowing water from upstream is routed through the reservoir, resembling natural riverine conditions (Emamgholizadeh, 2006). On the other hand, in terms of "flushing phases", the flushing process can be divided into two main types: with or without drawdown flushing operation. “Drawdown” is the lowering of the water levels in a reservoir.

1.2. Features and Limitations of Flushing

Generally, the effect of pressure flushing is quite local. Specifically, when the water stage in the reservoir is high, due to pressure flushing, only a local flushing cone is formed (for example see Fig. 2) and the flushing process is not very effective (Shen, 1999). Actually, in this case, the main function of the flushing cone is to reduce the sediment concentration around the entrance of intake and to prevent hydraulic structures from abrasion by sediments. By contrast, in free flushing, the reservoir usually should be emptied with riverine flow throughout the impoundment, thereby restoring high volumes of the reservoir's dead-storage capacity. For that reason, in most situations, free flushing is preferred over pressure flushing for achieving maximum flushing efficiency in the reservoir.

However, there are some special situations in which imposing the pressure flushing scenario is inevitable. An example of one such case is Dez dam in Iran. In Dez dam, sedimentation has caused the sediment level near the power intakes to increase significantly. In its operational period, a sedimentation rate of 15 to 20 MCM/year has caused the sediment level behind the dam to rise to 12 m below the power intakes (with a rate of 2 m/year) and the delta front to progress 0.5 to 1 km/year toward the dam. Currently, the major issue threatening the Dez dam is the continual accumulation of silt and clay in the reservoir near the dam. This situation poses a potential impact on the physical operations of the dam, especially regarding power generation. Considering this

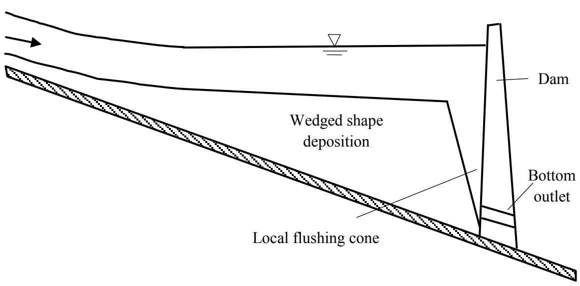

Figure 2. Local flushing cone formed in a wedged shape deposition due to pressure flushing (adapted from Shen, 1999)

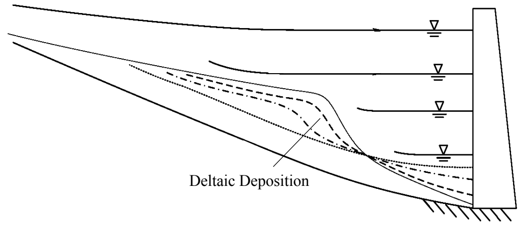

Figure 3. The changes in longitudinal profile of a deltaic deposition due to pressure flushing process (in the first stages) and free flushing (in the last stage) (Un, 2006)

problem and the particular operational features of Dez dam, which do not allow the operators to use efficient free flushing or any other quick method to control sedimentation, so far many attempts have been made to reduce the level of the deposition near the power intake. Among them are at least 7 attempts at pressure flushing as of 2005 (Emamgholizadeh et al., 2006).

Although the main effect of pressure flushing is limited to the flushing cone around the outlet, that cone can be developed by combining the pressure flushing process with an appropriate water level drawdown scenario. Fig. 4 shows a conceptual schematic of the flushing process under the wedge-shaped depositions in a presumed water level drawdown scenario. It can be seen clearly that the deposition zone has reached the dam site and, after opening the bottom outlet gate, the outflow erodes a stable flushing cone in front of the outlet. By lowering the water level from 0 to 1, the shape of the erosion in the region of the outlet has been changed to some extent. Subsequently, when the water surface level is about the same level as the bed surface near the gate (level 1 to level 2), the flowing water starts to erode the rim of the flushing cone and retrogressive erosion occurs toward the upstream direction (Lai, 1994).

1.3. Modeling of the Flushing

Numerical modeling of the reservoirs, either in the stage of design or during their operation, helps designers as well as operators to have a better operational management plan for the reservoir. This can be achieved by predicting the depositional behaviour of the reservoir and regulating practical guidelines for sediment management in the reservoir through a schedule of sediment flushing during the operation of the reservoir.

Literature review shows that many attempts have been devoted to modeling such cases by applying one- or two-dimensional numerical models. However, neither one- nor two-dimensional models are appropriate for studying the process of pressure flushing. In two-dimensional horizontal models, the basic assumption is that the distribution of velocity and the sediment concentration along the depth are uniform. However, it has been shown that, during the process of pressure flushing and after the opening of the bottom outlet, the velocity and sediment concentration near the outlet are

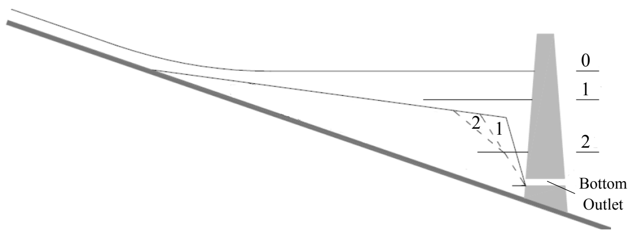

Figure 4. Retrograde erosion under condition of wedge shaped deposition (Lai, 1994; adapted from Jugović, 2009)

much higher than above levels, so the basic assumption of those models is not reasonable. Moreover, the modelling of the density currents, which happen mostly by stratification of the density, is not possible using 2-D horizontal models.

In two-dimensional vertical models, the results are more acceptable than in 2-D horizontal models. Still, even in these models, the main assumption is uniformity of velocity and sediment concentration along the width of the channel. Accordingly, considering that the velocity profile and the profile of sediment concentration are not uniform along the width of the reservoir (they peak near the outlet), they also cannot give fully satisfactory results.

To sum up, as pressure flushing is entirely a 3-D phenomenon in a very restricted area near the outlet and its duration is also rather short (which means less computational time would be needed for its simulation), modeling this process by a 3-D code could be an advantage. Conversely, for free flushing, which mimics the natural riverine condition and which is a longer process as well, employing a 2-D or 1-D model would be more reasonable.

1.4. The Purposes of This Paper

In the present study, a 3-D numerical model will be applied to examine the process of pressure flushing in a simplified reservoir silted in wedge-shaped deposition. The main purpose of this paper is to study the capabilities of a 3-D model to simulate this phenomenon by investigating the mechanism of the pressure flushing operation and describing the behaviour of the cone formation and retrograde erosion of the flushing cone under drawdown conditions.

2. METHODS AND PROCEDURES

2.1. Numerical Code

The numerical model used in this study is called SSIIM, an acronym for Sediment Simulation In Intakes with Multi-block option. SSIIM is available in two versions, allowing for both structured and unstructured grids to be used in the modeling process. Owing to the nature of the problem investigated in this study, the version 2 of SSIIM, which works with unstructured grids, was employed. SSIIM simulates the flow field by applying the Reynolds-averaged Navier-Stokes equations:

$$U_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial}{\partial x_j}(P\delta_{ij} + \rho\overline{u_i u_j}) \qquad (1)$$

and the continuity equation

$$\frac{\partial U_i}{\partial x_i} = 0 \qquad (2)$$

where ρ is the fluid density, δ_{ij} is the Kroneker delta, U_j are the components of local time averaged flow velocities, P is dynamic pressure, and $-\rho\overline{u_i u_j}$ are the turbulence Reynolds stresses (Olsen, 2002). As the turbulence in the flow affects the velocity, it is necessary to use an advanced turbulence model to handle a 3-D flow problem. In this study, turbulent stresses in the Reynolds-averaged equations will be closed by standard k- ε turbulence models. For discritization, the control volume is divided into finite volume and the governing equations are solved for each cell and each variable. The convection terms are discretized using the first order power law (POW) scheme. For velocity-pressure coupling, the SIMPLE algorithm is adopted. For boundary condition, the "inflow" boundary condition is applied to the inlet plane. The outlet of the channel is defined using the "zero gradient" boundary condition. The side walls are solid boundaries and the "wall" boundary condition is used for these boundaries. For the k- ε turbulence model, the standard wall function is applied to bridge the near wall boundaries and turbulent regions. The suspended sediment transport is calculated with the convection-diffusion equation. The boundary condition for sediment concentration in the cell closest to the bed is determined by the formula given by van Rijn:

$$C_{bed} = 0.015\frac{d_{50}^{0.7}}{a}\cdot\frac{\left[\frac{\tau_0-\tau_c}{\tau_c}\right]^{1.5}}{\left[\frac{\rho_s-\rho_w}{\rho_w}\cdot\frac{g}{\nu^2}\right]^{0.1}} \qquad (3)$$

where C_{bed} is the equilibrium bed sediment concentration (volume fraction); d is the diameter of the sediment particle; a is the reference level; τ_0 is the bed shear stress; τ_c is the critical bed shear stress for the movement of sediment particles; ρ_s is the density of the sediment; ν is the kinematic viscosity of water; and g is acceleration due to gravity. The concentration determined by (3) could be extrapolated by the Rouse equation to calculate the values at the required level (Bhuiyan and Olsen, 2002). To calculate the bed load, SSIIM uses the van Rijn equation:

$$\frac{q_b}{d_{50}^{1.5}\sqrt{(s-1)g}} = 0.053\frac{T^{2.1}}{D_*^{0.3}} \quad (4)$$

in which q_b is the rate of bed load per width, d_{50} is the mean diameter of the sediment, s is the specific density parameter, D_* is the non-dimensional particle parameter, and T is the transport parameter, which can be achieved by:

$$D_* = d_{50}\left(\frac{(s-1)g}{\nu^2}\right)^{\frac{1}{3}} \quad (5)$$

$$T = \frac{\tau-\tau_c}{\tau_c} = \frac{u^2_* - u^2_{*,c}}{u^2_{*,c}} \quad (6)$$

where u_* is bed shear stress ($u_* = \frac{\bar{u}\sqrt{g}}{C}$ in which C is Chezy coefficient and $\bar{u}$ is the mean velocity) and $u_{*,c}$ is the critical shear stress (from Shields diagram). Changes in bed levels are calculated by applying the continuity equation and the conservation of mass of sediment (Exner equation) to determine the continuity defect in the bed cells. On a sloping bed, the critical shear stress for sediment movement is different than that for a horizontal bed. The decrease in critical shear stress for the sediment particles was determined by the Brooks equation:

$$K = -\frac{\sin\phi\sin\alpha}{\tan\theta} + \sqrt{\left(\frac{\sin\phi\sin\alpha}{\tan\theta}\right)^2 + \cos^2\phi\left[1-\left(\frac{\tan\phi}{\tan\theta}\right)^2\right]} \quad (7)$$

where α is the angle between the flow direction and a line normal to the bed plane; ϕ is the slope angle and θ is a slope parameter, which is generally larger than the geotechnical angle of repose for the sediment. The factor K is calculated and multiplied by the critical shear stress for a horizontal surface to give the effective critical shear stress for a sediment particle (Bhuiyan and Olsen, 2002).

2.2. Model Geometry and the Configuration of the Model

The characteristics of the case study are adapted from a simplified reservoir geometry that was set up by Emamgholizadeh et al. (2007): 7m long, 1.5m wide and 1.5m high. Up to 30 cm above the level of the bottom outlet of the reservoir was filled with the sand as non-cohesive sediment with the specific gravity of 2.65 and a mean diameter of 1.2 mm. The low level outlet was an individual circular opening of 5 cm. A grid made up of 150 longitudinal sections, 34 cross sections and 11 vertical layers was generated to represent the geometry of the domain. At the bottom of the reservoir, a non-erodible layer was applied. In the experiments, the bottom outlet was installed a little bit higher than the level of tank's non-erodible bed. However, in the numerical simulation, to simplify the modeling and to avoid instability in the calculation, the outlet was modelled in the level of tank's non-erodible bed.

Modeling was done in two main steps. The first stage simulated the formation of the flushing cone in front of the bottom outlet due to pressure flushing by assuming the high water level of 80 cm and 110 cm and water discharge equal to 4.5 and 6 lit/s respectively. The results were used to calibrate the numerical simulation by comparing them with available experimental data. In the second stage and after the flushing zone reaches equilibrium state, the water level was reduced in a stepwise drawdown scenario from an initial high (operational reservoir) water level of 80 cm (and a constant flow rate) to the level near the sediment layer, in order to monitor the water level at which sediment movement begins and the retrogressive erosion of the flushing cone toward the upstream occurs.

2.3. Calibration of the Model

First, it was necessary to calibrate some effective parameters for the model. Accordingly, the initial geometry of the domain was generated based on the points mentioned in section 2.2. Since in the experimental study the initial state of the sediment layer was located above the top level of the outlet, to satisfy the continuity equation in the numerical model, the initial geometry was modified so that the continuity between inlet boundary and outlet boundary would be satisfied. Then, many trails were made to obtain the proper parameters, in particular the time step and bed roughness, and in each stage the results were compared with available dataset. Finally, the model with the time step of 60 s and Ks=5*d50=6 mm (in which Ks is the roughness coefficient) showed satisfactory results, which are summarized in Table 1. As shown, the model managed to simulate the pressure flushing with about 15% difference in estimating the volume of flushing zone. Considering the several uncertainties that remained in the numerical model that might affect the result of the model, including the empirical equations used in calculation of sediment transport, calibrating the bed roughness more precisely (which required more trial and error, but due to time limitations was disregarded in this study), this difference between simulated results compared to the experimental data can be quite acceptable.

3. RESULTS AND DISCUSSION

Figure 6 shows a 3-D view of the flushing zone after implementing pressure flushing. As mentioned earlier, the main goal of pressure flushing is to reduce the sediment concentration around the entrance of the intake

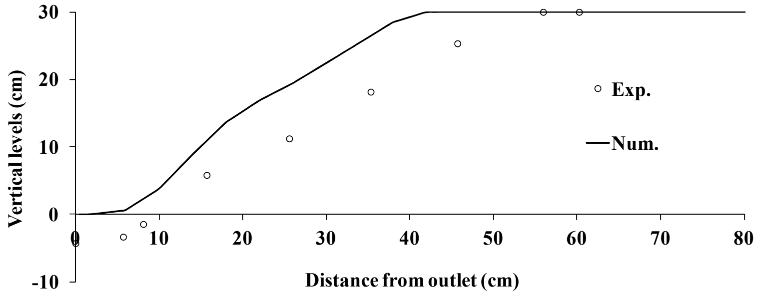

Figure 5. Comparison of the longitudinal bed profile in front of the bottom outlet

Table 1. The volume of flushing zone for different high water levels (h_w) and their corresponding flow discharges

Characteristics of the flow	Volume of flushing zone (cm3)	
	3D model	Exp.
Q=4.5 lit/s - h_w= 80 cm	33750	36588
Q=6.0 lit/s - h_w= 110 cm	35137	38444
Mean error (%)	8.15	

and to prevent hydraulic structures from abrasion by sediments. As expected, the desilting of the deposit has been limited to a local cone near the outlet, so the results of the numerical model managed to prove this function of the pressure flushing process. Nonetheless, to achieve a flushing channel along the reservoir and the desilting of high volumes of the reservoir's sediment deposits, reducing the water level to free-flushing levels may be required.

Figure 7 illustrates the streamlines of the flow near the bed of the reservoir. As shown in this figure, the streamlines of flow are quite uniform until they reach the flushing cone. Conversely, in the regions next to the cone, all the streamlines have deviated due to the presence of the button outlet.

Although the effect of pressure flushing has proven to be local, from this point on and into the second stage, this study attempts to model the effect of a supposed water level drawdown on the same cone. To do so, a stepwise water level drawdown was applied to the model from 80 cm (high operational water level in the reservoir) to 40 cm, and a series of new models were started based on the deformed grid of the previous stage.

Figure 8 shows the result of the modeling of the water level drawdown scenario. As can be seen in this figure, by lowering the water level from 80 cm to 60 cm, the rim of the cone has been eroded and those sediments have been transported into the crater, progressing toward filling it. Indeed, in this stage, the diameter of the flushing funnel has reduced and the front face of the funnel has moved toward the outlet. In addition, the slope of the funnel in front of the outlet has become steeper. In the next stage of water drawdown, the study compares

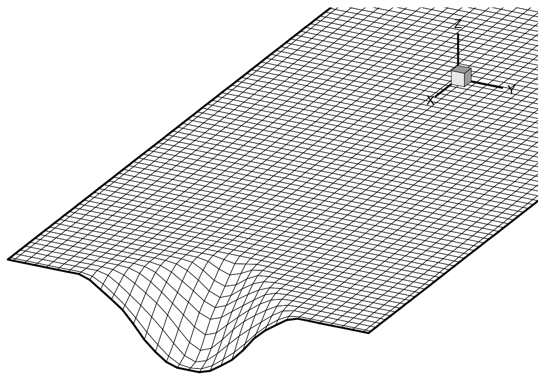

Figure 6. A 3D view of cone formed around the bottom outlet of the reservoir after the pressure flushing process

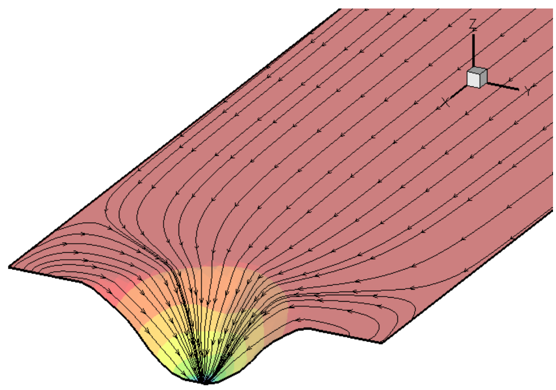

Figure 7. A Streamlines of the flow near the bed of the reservoir.

the profile of the bed for water levels of 60 cm and 40 cm. It can be observed that, although the erosion of the crater's rim has resulted in lowering the level of the top face of the flushing funnel, a process of retrograde erosion toward the upstream has simultaneously started the formation of a kind of flushing channel. Therefore, the pattern of desilting in this step is quite different from the case in which the pressure flushing was done at the high operational water level. In other words, operating the pressure flushing at a high water level was able to produce only a very local and limited flushing cone around the outlet. In contrast, applying a drawdown scenario as shown in Fig. 8, would make it possible to increase the rate and volume of desilting of the reservoir.

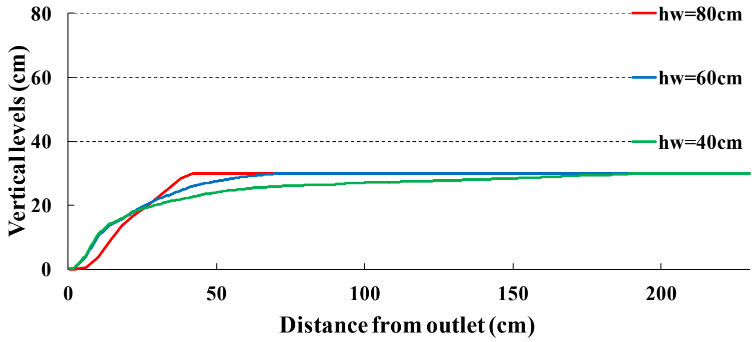

Figure 8. Development of retrogressive flushing during the water level drawdown scenario.

This would serve as a good alternative for the flushing of reservoirs in cases where the free flushing operation is not preferable. Another point that should be mentioned here is that achieving the circumstances under which retrogressive erosion occurs was only possible by lowering the water level considerably, to a level very close to the sediment deposit. This means there is a minimum water level for which sediment movement intensifies and the drag forces of the flow around the outlet are capable of beginning the retrogressive erosion toward the upstream.

4. CONCLUSION

3-D numerical modelling of the pressure flushing of a simplified reservoir showed that the effects of flushing a reservoir at a high operational water level is limited to a very restricted zone and formation of a local flushing cone around the outlet. However, applying a drawdown scenario of water level increases the efficiency of the flushing and achieves the higher volume of desilting of the sediment deposit. Nevertheless, even in the drawdown process, there is a specific water level in which the retrogressive progress of the erosion can happen.

REFERENCES

Annandale, G.W. (2001): Reservoir conservation and sediment management, World Bank,Washington D.C.

Brabben, T.E. (1988): Reservoir Desilting Methods. Technical Note OD/TN 32, HR Wallingford, Wallingford.

Brown, C.B. (1943): The Control of Reservoir Silting, United State Department of Agriculture, Miscellaneous Publication No. 521, Washington, D.C.

Bhuiyan, F., & Olsen, N. R. B. (2002): Three-dimensional numerical modeling of flow and scour around spur-dikes, Proceedings of the Fifth International Conference on Hydroinformatics, Cardiff, UK.

Emamgholizadeh, S., Bina, M. Fathi-Moghadam and M., Ghomeshi (2006): Investigation and Evaluation of the Pressure Flushing through Storage Reservoir, ARPN Journal of Engineering and Applied Science, 1:4, pp. 7-16

Emamgholizadeh, S., Bina, M., Ghomeshi, M., & Jahani, H. (2007): The investigation and evaluation of the pressure flushing through storage reservoirs using physical models (in Persian), Iran-Water Resources Research, 3:1, pp. 68-79.

Fan, J. (1985a): Methods of Computing Sedimentation in Lake and Reservoir. A contribution to the International Hydrological Programme, IHP-II Project A. 2.6.1 Panel, S. Bruk, ed., Unesco, Paris, pp. 65-164.

Fan, J. (1985b): Lecture Notes of the Training Course on Reservoir Sedimentation. Series of Publication IRTCES, Beijing, pp. II.1- II.96.

Jugović, C. J., Strohmeier, S., Schuster, G., and Nachtnebel, H. P. (2009): Hydraulic Flushing of Alpine Reservoirs – Model Study, International Symposium on Water Management and Hydraulic Engineering, Ohrid/Macedonia.

Kantoush, S., Sumi, T., Suzuki, T., and Murasaki, M. (2010): Impacts of sediment flushing on channel evolution and morphological processes: Case study of the Kurobe River, Japan, Proceeding of the River Flow 2010.

Lai, J. S. (1994): Hydraulic Flushing for Reservoir Desiltation, Dissertation, University of California at Berkley.

Lai, J.S. and Shen, H.W. (1996): Flushing Sediment Through Reservoirs, Journal of Hydraulic Research, 34;2, pp. 237-255.

Liu, J., Minami, S., Otsuki, H., Liu, B. and Ashida, K. (2004): Prediction of Concerted Sediment Flushing, Journal of Hydraulics Engineering, 130:11, pp. 1089-1096.

Mahmood, K. (1987): Reservoir sedimentation: Impact, Extent, and Mitigation, World Bank Technical Paper Number 71, Washington, D.C.

Morris, G.L. and Fan, J. (1997): Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoir, and Watersheds for Sustainable Use, McGraw Hill, New York.

Olsen, N.R.B. (2002): A 3D numerical model for simulation of sediment movements in water intakes with multi-block option. User's Manual, NTNU, Norway.

Shen, H. W. (1999): Flushing sediment through reservoirs, Journal of Hydraulic Research, 37:6

Un, J. (2006): Numerical Model for Sediment Flusing at the Nakdong River Estuary Barrage, Dissertation, Colorado State University

Yoon, Y.N. (1992): The State and the Perspective of the Direct Sediment Removal Methods from Reservoirs, International Journal of Sediment Research, 7:2), pp. 99-116.