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Study of dam sediment distribution using experimental area-reduction method Case study: Karun Dam

Rakhmat Yusuf[1], Aan Komariah[1], Dedy Achmad Kurniady[1], Mardiani Mardiani[1], Jumintono Jumintono[2], Khaldoon T. Falih[3], Oleg V. Kabanov[4], Surendar Aravindhan[5], Mustafa Mohammed Kadhim[6]

[1] Universitas Pendidikan Indonesia, Department of Civil Engineering, Jl. Dr. Setiabudi No. 229, Isola, Kec. Sukasari, Bandung, Jawa Barat 40154, Indonesia

[2] Universiti Tun Hussein Onn Malaysia, Faculty of Technical and Vocational Education, Batu Pahat, Johor, Malaysia

[3] Al-Ayen University, Scientific Research Center, New Era and Development in Civil Engineering Research Group, Dhi-Qar, Iraq

[4] National Research Ogarev Mordovia State University, Department of Electronics and Electrical Engineering, Republic of Mordovia, Saransk, Russia

[5] Saveetha Institute of Medical and Technical Sciences, Department of Pharmacology, Chennai, India

[6] Al-Kut University College, School of Science and Engineering, Kut, Wasit, Iraq

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Abstract: Dam construction is one of the measures that is inevitable in many cases and must be done to supply drinking water, agricultural uses and electricity generation. There are many challenges to a successful dam project, and the managers of each project must consider the appropriate solutions for them. One of the studies that is done in dam design is sedimentation in dam reservoirs. The experimental area-reduction method is a very common technique that obtains the sediment distribution in depth and longitudinal profile. This technique shows that sediment accumulation is not limited to the bottom reservoirs. Sediment accumulation in a reservoir is usually distributed below the top of the protection reservoir or normal water level. In this study, the distribution of sediment in the reservoir of Karun Dam after a period of 65 years has been done using the experimental area-reduction method. Elevation–volume and elevation–area curves of the dam reservoir are obtained after the useful life of the dam and sediment deposition. The results showed that after 65 years, $106.47 \cdot 10^6$ m^3 of sediment is deposited in the reservoir of the dam and the useful volume of the reservoir is significantly reduced. Also, up to a height of 36.4 m, the dam reservoir is filled with sediment. Therefore, no valve should be placed up to this height.

Keywords: area-reduction method, dam reservoir, distribution of sediment, elevation–area curve, elevation–volume curve

INTRODUCTION

It is very important to predict the amount of sediment entering the dam reservoir and how it is distributed in the dam reservoir during the operation of the reservoir [Nourani *et al.* 2019]. Sediment effects should be considered in the planning, design, operation and maintenance of the dam [Beltaos, Burrell 2021; Vona *et al.* 2020]. Sedimentation will have many negative effects [Schleiss *et al.* 2016; Wang *et al.* 2005]. One of the effects of sedimentation is increased evaporation. Another effect of sedimentation is rising of the reservoir floor and flooding of lands. Sedimentation of dam reservoirs reduces the effect of flood control by the reservoir. Accumulation of sediment near the dam site may reduce its stability [Fourvel *et al.* 2018]. Erosion and foaming downstream of the dam may cause the dam foundation to fall out and become unstable.

Sediment distribution studies in dam reservoirs are important from three perspectives: (i) to prevent the reduction of the main capacity of the dam reservoir during its useful life, a volume for sedimentation of sediments is always considered; (ii) it is very important to study the distribution of incoming sediments to dam reservoirs to determine the threshold level of deep valves and the location of sluices; (iii) in dam operation studies, an average of sediment accumulation over economic life can be used to determine the water available for supply [Cimorelli *et al.* 2021; Dutta, Sen 2016].

When sediment accumulation is predicted to be more than 5% of the dam reservoir capacity, we need to allocate space to store sediment. A period of 100 years is usually considered to predict sediment accumulation.

The most important methods proposed to calculate the sediment distribution in dam reservoirs are: experimental methods of area-reduction and area-increment [Torabi *et al.* 2015]. The area-reduction method is a mathematical method based on observational principles in reservoirs. In this method, reservoirs are geometrically divided into four types. For all reservoir types, parameters are achieved based on a limited number of reservoirs which leads to large scale errors for prediction of this method. So suitable parameters can be achieved in dams that are in operation and hydrography of reservoir is carried out at least once. In other words, the method can be calibrated for the reservoir [Issa *et al.* 2017]. In this study, while comprehensively introducing the area-reduction method, sediment distribution in the reservoir of Karun Dam has been done. Also, the elevation–volume and elevation–area curves of the dam reservoir before and after 65 years of sedimentation have been compared.

MATERIALS AND METHODS

DATA

Karun Dam is located in the southwest of Iran (31.5995° N, 50.4725° E). The Karun Dam is a hydroelectric dam on the Karun River located in the province of Khuzestan, Iran. The volume of the studied reservoir is $428.210 \cdot 10^6$ m^3. The study of sediment distribution after a period of 65 years is considered. The annual inflow is $1,100 \cdot 10^6$ m^3. The annual amount of sediment that enters the reservoir is $2,100 \cdot 10^3$ Mg. The reservoir is usually operated normally moderate to considerable reservoir drawdown. It should be noted that 23% of the sediment is clay, 40% of the sediment is silt and 37% of the sediment is sand.

EXPERIMENTAL METHOD OF AREA-REDUCTION

In each sediment distribution study, we need three types of information, which are:
– trap efficiency,
– sediment density,
– mathematical method for determining the sediment distribution in a dam reservoir.

In this study, the area-reduction method has been used. All three will be explained in detail below.

Trap efficiency

Trap efficiency of a dam is defined as the ratio of sediment deposited to the total input sediment flow. Brune [1953] proposed a set of curves using the capacity–inflow relationship of reservoirs. Churchill [1947] presented the relationship between the percentage of sediment entering the reservoir and the sedimentation index of the reservoir. The Brune method is generally applicable to large reservoirs and the Churchill method to small reservoirs.

Sediment density

Lara and Pemberton [1963] used about 1,300 samples to determine the mathematical equation that gives the amount of changes in sediment density for different types of operation. Equation (1) is the equation extracted by these researchers.

$$W = W_c P_c + W_m P_m + W_s P_s \tag{1}$$

where: W = density (kg·m^{-3}), P_c, P_m, and P_s = percentages of clay, silt and sand, respectively; W_c, W_m, and W_s = density coefficients of clay, silt and sand (kg·m^{-3}).

It should be noted that in Equation (1), we need the values W_c, W_m, and W_s. These values are determined from “Design of small dams” book [USBR 1987].

Note that Equation (1) gives the initial sediment density. In order to calculate the average density of all sediments deposited in T year of operation, Equation (2) should be used.

$$W_T = W_1 + 0.4343K\left[\frac{T}{T-1}(\log_e T) - 1\right] \tag{2}$$

where: W_1 = the initial density calculated from Equation (1), W_T = average density after T year of operation, K = a constant obtained from Equation (3), K_c, K_m, and K_s = constants for clay, silt and sand.

It should be noted that the values of are also obtained from “Design of small dams” book [USBR 1987].

$$K = K_c P_c + K_m P_m + K_s P_s \tag{3}$$

Mathematical method for determining sediment distribution

When the amount of sediment is below the normal water level, the experimental area-reduction method is used to estimate the distribution. According to this method, sediment distribution depends on: 1) the method according to which the reservoir is operated, 2) the texture and dimensions of the sediment particles, 3) the shape of the reservoir and 4) the volume of sediments deposited in the reservoir. However, the third case, the shape of the reservoir, has been accepted as the main criterion. The shape of the reservoir is determined by the inverse of the slope of the depth–capacity diagram. The classification of reservoirs is based on the shape of the tank as shown in “Design of small dams” book [USBR 1987].

The design curves can be used to predict future sediment distribution at depth. In these curves, the type of distribution must first be determined. Given the same importance for reservoir operation and reservoir shape, the type of distribution can be achieved using the rules of USBR [1987].

In summary, the steps for determining the sediment distribution in the reservoir are as follows:
1) determining the rate of sediment accumulation,
2) calculating the level of sediment deposited in the dam,
3) distribution of a certain volume of sediment.

It should be noted that the relative sediment area follows Equations (4)–(7) for a variety of design curves. In these relations, *a* refers to the relative area of the sediment and *p* to the relative depth of the reservoir measured from the bottom.

$$\text{Type I}: \quad \mathrm{a} = 5.074\mathrm{p}^{1.85}(1-\mathrm{p})^{0.35} \tag{4}$$

$$\text{Type II}: \quad \mathrm{a} = 2.487\mathrm{p}^{0.57}(1-\mathrm{p})^{0.41} \tag{5}$$

$$\text{Type III}: \quad \mathrm{a} = 16.967\mathrm{p}^{1.15}(1-\mathrm{p})^{2.32} \tag{6}$$

$$\text{Type IV}: \quad \mathrm{a} = 1.486\mathrm{p}^{-0.25}(1-\mathrm{p})^{1.34} \tag{7}$$

RESULTS AND DISCUSSION

STEP 1

In order to solve this problem, the trap efficiency of the reservoir must first be obtained. Due to the significant reservoir volume, in this study the Brune curve is used to calculate trap efficiency. In this regard, the ratio of reservoir capacity (V_r) to average annual inflow (Q_{av}) should be calculated first:

$$\frac{V_r}{Q_{\mathrm{av}}} = 0.389$$

It should be noted that the trap efficiency value was approximated 95%. This means that 95% of the total input sediment in the reservoir, or about 1995 mln kg·y^{-1}, is deposited.

STEP 2

In the second step, in order to calculate the volume of incoming sediment, the density of deposited sediments should be obtained using Equations (1)–(3). After that, the total volume of sediment deposited in the reservoir during 65 years should be calculated.

STEP 3

Next, in order to identify the weighted type, the type of reservoir shape must be found. Note that the depth–capacity diagram on the logarithmic scale is not a line. But if we consider the slope of the line that connects the beginning point to the end, we can calculate the approximate value of *m* (inverse of the slope of the depth–capacity diagram on a logarithmic scale) *m* as follows:

$$m = \frac{\log V_r}{\log h_r} = 2.7$$

where: h_r = reservoir depth.

Therefore, according to the value of *m*, the shape of the reservoir is in the category of flood plain-foothill and the type of reservoir is II. Now, according to the type of operation, weighted type is also of type II.

STEP 4

The next step in studying the sediment distribution is to find the level at which the sediment distribution begins in the reservoir. From the beginning of the reservoir to its new zero level, the reservoir is completely filled with sediment. From the new zero level onwards, sediment distribution begins. For this purpose, we must first use Equation (8) and find the values of *F* (dimensionless function) for 65 years at different levels.

$$F = \frac{S - V_h}{HA_h} \tag{8}$$

where: *S* = the total volume of sediment deposited in the reservoir, V_h and A_h = the capacity and area of the reservoir at the level of *h*, respectively, *H* = the total depth of sediment.

Then obtain the intersection of the *F*-relative depth curve, and the type II curve. The relative depth of the collision of these two curves will give the value P_0. Multiplying P_0 in the depth of the reservoir and adding it to the lowest reservoir level, a level will be obtained from which the sediment will start to distribute.

According to Figure 1, the value of P_0 was calculated to be 0.383. Therefore, considering that the floor level of the reservoir and the depth of the reservoir are equal to 1240 m and 95 m, respectively, the level from which the sediment is distributed is approximately 1276.4·(0.383·95 + 1240) m.

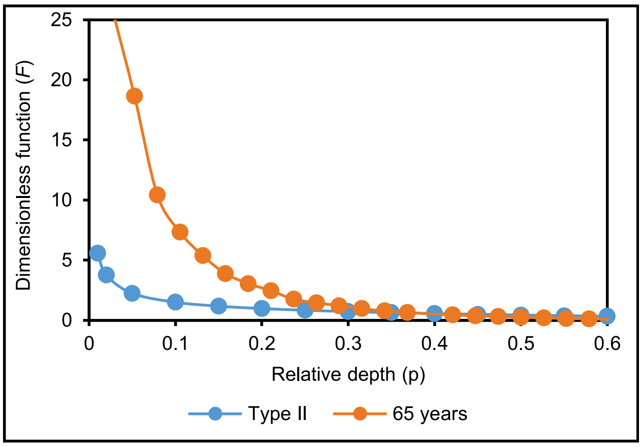

Fig. 1. Curves to determine the depth of sediments in the dam reservoir after 65 years; source: own study

STEP 5

In the next step, Equations (9) and (10) can be used to predict the volume distribution and future sediment level at depth.

$$S_{y,T} = \int_0^{y_0} A_y \mathrm{d}y + \int_{y_0}^{y} Ja_y \mathrm{d}y \tag{9}$$

$$A_{y,T} = Ja_y \tag{10}$$

where: y_0 = the reservoir depth from floor level to zero level (which according to step 4 is 36.4 m), A_y = reservoir area at depth *y* of reservoir and at the present time, a_y = the relative area of reservoir sediments at depth *y* and at the present time (calculated from Eq. (5)), S_y = the cumulative volume of sediment at depth y at present time, J = constant coefficient calculated from Equation (11), $S_{y,T}$ and $A_{y,T}$ = the reservoir volume and area at depth p after T years, respectively.

By placing Equation (5) in Equation (9), Equation (12) is achievable for calculating sediment at depths greater than p_0. Note that the integral of Equation (12) can only be calculated by numerical methods:

$$J = \frac{A_0}{a_0} \tag{11}$$

$$S = 19.45 + 1.35 \cdot 2.487 \int_{20}^{p} \left(\frac{p}{95}\right)^{0.57} \left(1 - \frac{p}{95}\right)^{0.41} \tag{12}$$

It should be noted that we will always expect the amount of sediment obtained from Equation (9) at the normal level of the reservoir to be equal to the amount of sediment calculated in the second step. If the error value in this case is more than 1%, the value of J must be corrected with Equation (13) and the calculations performed again.

$$J_{\text{modified}} = J \frac{S}{S_1} \tag{13}$$

where: S = the actual volume of sediment (is equivalent to $107.47{\cdot}10^6$ m^3), S_1 = the total volume of sediment calculated in the previously.

Figure 2 shows a comparison between the elevation–volume and elevation–area curves of the reservoir at the present time and after 65 years. It should be noted that after the second iteration, convergence took place. As you can see in Figure 1, over 65 years, the area and volume of the reservoir in the depth of the reservoir is decreasing. This decrease is greater at lower reservoir elevations than at higher elevations.

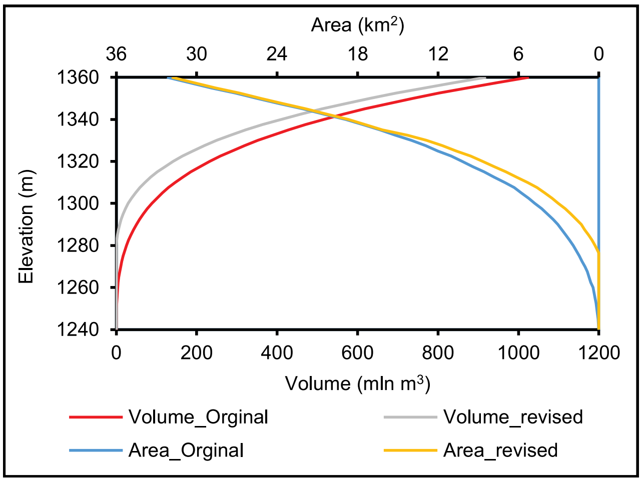

Fig. 2. Elevation–volume and elevation–area curve of the reservoir in the present time and after 65 years; source: own study

CONCLUSIONS

In this study, the sediment distribution of Karun Dam after 65 years has been done using the area reduction method. Five general steps have been taken to distribute sediment at different elevations of the dam. In the first step, the trap efficiency of the dam reservoir was obtained. This quantity indicates how much of the sediment mass entering the reservoir is deposited in the reservoir. In the second step, the density of sediments deposited on the bottom of the reservoir was calculated. By calculating the density, the amount of sediment volume was obtained. In the third step, based on the shape of the reservoir and the type of operation, the weighted type was determined. In the fourth step, a new zero elevation of the dam reservoir was obtained. Because from the old zero elevation to the new zero elevation, the reservoir is full of sediment. In the last step (fifth step), the reservoir sediment was distributed from the new zero elevation to the normal level. After performing five general steps, the elevation–area and elevation–volume curves of the reservoir were obtained after 65 years. The results showed that at the end of 65 years, the amount of $107.47{\cdot}10^6$ m^3 of sediment is deposited in the reservoir of the dam.

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