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ORIGINAL ARTICLE

Laboratory investigation on erosion threshold shear stress of cohesive sediment in Karkheh Dam

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Abstract

The awareness of the transmission of the sticky sediments for the development and maintenance of reservoirs and water transfer network is very important. This research was carried out to recognize and understand the dynamic behavior of fine-sticky sediments to obtain the necessary information for the Karkheh dam reservoir management. Sediment samples were taken from the four different points located in the dam reservoir. Liquidity and plasticity behaviors and their indices of the samples that were combined together were determined by doing the Atterberg limits experiment. To investigate the initial erosion threshold shear stress, the impact of consolidation and sediment depth were examined by cylindrical settling columns. Using a circular flume in, Shahrekord University Lab, the concentration process, changes of eroded sediments, shear stress threshold of erosion, erosion rates, etc. in different consolidation periods (3, 14 and 30 days) were studied. The results showed that the concentration of eroded sediments is a function of time for the consolidation of reservoir sediment and bed shear stress and also observed that the duration of consolidation time is an effective factor on critical erosion shear stress. So, the threshold shear stress values for consolidation time of 3, 14 and 30 days were, 0.16, 0.22, 0.31 N/m^2, respectively. The results of the erosion rate suggest an inverse relationship between this parameter and the life of the settled sediments based on the results the best flow shear stress for sediment removal by flashing from the Karkheh dam reservoir should be greater than 0.31 N/m^2.

Keywords Critical shear stress · Sediment · Erosion · Dam

Introduction

Awareness of the characteristics of the sediment and the circumstances in which the sediments in the river environment settled down or eroded is very important for the recognition and management of sedimentation in rivers and reservoirs. With the construction of the dam on the Rivers upstream and downstream of the dam, the connection is loose and the balance of sediment transfer is also interrupted and more disarrangement took place within entrapped sediments in the positioned dam reservoir. The International Committee on large dams (ICOLD) information on sedimentation in dams

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is considered to be very important to provide a long-term solution for maintenance and use. The Problems of sedimentation in reservoirs can be listed as reducing the storage capacity of the reservoirs, damage to plant and Hydromechanical equipment, reduce energy capacity, reduce water quality and its effects on downstream (Partheniades 2009; Fattahi Nafchi et al. 2021a, b; Abdollahi et al. 2021; Ostad-Ali-Askari et al. 2020a). Hydraulic transmission of fine sediment generally consists of the processes of settling, consolidation, and erosion. The cohesion of the sediment causes the small particles to bind together and collide with other particles or other flocks to form larger flocks (Huang et al. 2006; Ostad-Ali-Askari et al. 2021a; Fatahi Nafchi et al. 2021; Talebmorad et al. 2020; Talebmorad et al. 2021). The great flocks settled more rapidly than the smaller one and result to form stratification bed with a substrate layer that is placed on the upper layer of fine particles. The settled particles in under layers will be consolidated gradually. The particles settled in the upper layers are facing the possibility of further erosion to come back into the suspended mode (Krestenitis et al. 2007; Derakhshannia et al. 2020; Vanani et al. 2017; Ostad-Ali-Askari et al 2018; Salehi-Hafshejani et al. 2019; Pirnazar et al. 2018). The settled particles will form a saturated sedimentary bed. After the formation of the sedimentary bed, the sediment consolidation phase is started and the settled sediments will be compacted. Behavioral characteristics of sediments can be changed when they compacted and the parameters used to describe the cohesive sediment based on the specific bulk density may also change. Usually for fine sediment two types of primary and secondary consolidation are considered. The initial consolidation of sediments is due to their weight. When the weight of the particles over the force of pore pressure the initial consolidation is occurring. Secondary consolidation will happen due to the plastic deformation of the substrate, under an extra overload with a fixed rate. This process will be started during the initial consolidation and maybe longed for weeks or months after that. Consolidate under the weight of cohesive sediment is a complex phenomenon that is a function of a variety of processes and physical variables. Typically, two types of tests including the settling column and centrifuges for consolidation under the weight of the particles have been applied. Settled and consolidated sediments will be exposed to the erosion process according to the amount of turbulence and hydrodynamic features of the flow. The erodibility of cohesive sediment is controlled by a variety of parameters. Some of those are the size of the particles, the composition of minerals, organics, salinity, PH, biological processes, and the bed resistance (consolidation) (Mhashhash et al. 2018; Amelia et al. 2010; Giardino et al. 2009; Wang 2002; Ostad-Ali-Askari et al. 2021b; Javadinejad et al. 2021). On the erosion of the cohesive sediments, single-particle and small masses (flocks) separate from the biomass of soil by forces of hydrodynamic such as lift and drag forces. Tests of Roberts et al. (1998) to investigate the influence of the particle size and density on erosion rates showed that the rate of erosion tightly depends on particle density, while this situation for a coarse particle cannot be seen easily. As well as for fine-grained particles observed that, for a specific density and shear stresses, by increasing the diameter of the cohesive sediment the rate of erosion was quickly increased and after reaching a maximum amount, for coarse particles, this amount was reduced (Huang et al. 2006). According to Rinaldi and Casagli (1999), erosion is a function of the average speed of the current, depth of flow and the ratio of shear stress of stream to the shear stress threshold erosion. Threshold erosion shear stress is one of the most important parameters in the model of transferring the cohesive sediment. For the cohesive sediment, the amount of critical shear stress for erosion is greater than settling critical shear stress (Huang et al. 2006; Manning and Schoellhamer 2013; Golian et al. 2020). Erosion and sedimentation for the cohesive sediment cannot happen at any shear stress simultaneously. The reason is that when the cohesive sediment is settling electrochemical and biological processes cause the particle to be connected to the bed. So larger shear stress for remobilization of these particles than when settled have been required since in addition to overcome mass transfer of the particles and to become suspended again the adhesion force should also overcome (Krishnappan 2006; Ostad-Ali-Askari et al. 2017a; Javadinejad et al. 2018; Ostad-Ali-Askari et al. 2020b). Perhaps the works of Partheniades (1965) are the first classified experiments about the threshold erosion shear stress of the cohesive sediment. This researcher was performing two tests series in a direct rectangular channel with the sediments of San Francisco golf. The first experiment in the series was done with real density model for sediments, while the second test in the series was to let the sediments to be settled and consolidate. The results of both experiments showed that in the smallest amount of bed shear stress the erosion rate is small but nonzero. Former researchers believe this fact and suggest that the erosion threshold shear stress should not exist or is very small (Winterwerp 2007; Ostad-Ali-Askari et al. 2017b; Javadinejad et al. 2019). Many researchers in the 70 and 80 decades using circle flumes reviewed the process of cohesive sediment erosion and presented different models for erosion rates that some of them should be introduced hereunder. According to Samadi-Boroujeni et al. (2005), and Maa et al. (2008) related the rate of erosion (ε) at a depth of 202 m of Puget Sound in the Washington State to the bed shear stress (τ) as a power function in the Eq. (1):

$$\varepsilon = \alpha\tau^{\beta}. \tag{1}$$

In which α and β are practical coefficients.

According to the same work, Ashish (2014) considered the bed sediments erosion as the mass of displaced sediments by the shear stress and presented the Eq. (2) as follows:

$$E = \varepsilon\left(\tau_{\mathrm{b}} - \tau_{\mathrm{s}}\right), \quad (2)$$

where E is the erosion rate, ε erosion coefficient, τ_b bed shear stress and τ_s resistance bed stress.

Wang (2002) with the use of an interactive model of the wave—flow, estimated the critical shear stress of sediment erosion of America's Long Island to be 0.4 N/m^2. Lumborg (2005) with the use of numerical methods and model MIKE3 reported that the critical shear stress erosion of sediments of the Baltic Sea on the border of Sweden and Denmark is more than 0.5 N/m^2. Droppo et al. (2008) measured the shear strength of cohesive sediment with 5 discrete groups of water for different courses of consolidating and bed shear stress. He received that the durations of consolidation are effective on bed erosion of cohesive sediments but biological processes have a more powerful role in the stability control of the bed. Stone and Krishnappan (2003) performed a study on the impact on the biological stability of sediments in two rivers of South Alberta and found that the development of a particular biofilm in sediments pass through the volcanic flows is more feasible. The critical shear stress for the erosion of sediments taken from the lava of the volcano effect is 1.6–1.8 times larger than the sediment not affected by Lava. Glasbergen (2014) investigated the properties of cohesive sediment transfer of the Albu River basin in Canada using a rotating flume with a diameter of 5 m with a flatbed. According to this investigation, the extent of the critical shear stress for the erosion of cohesive sediment was 0.212 and 0.115 N/m^2, respectively, for the period of consolidation of 39 and 113 h. The critical shear stress for the erosion of the sediments of the Albu River was roughly two times greater than the critical shear stress for the settling. The results were in agreement with studies of Stone and Krishnappan (2003); Milburn and Krishnappan (2003). Droppo et al. (2015) to determine the specifications of the erosion, sediment transport and accumulation of cohesive sediment and investigate the effects of adherent bacteria community on erosion, sediment accumulation and transfer experiments in a rotating flume with a diameter of 2 m and duration of 1, 3 and 7 days were performed. The results of these researchers showed the bed critical shear stress for the occurrence of erosion varied from 0.05 to 0.19 Pascal (for a period of up to 7 days). The consolidation also increased with the passing of time and depth increasing. It was also observed that the structure of the eroded sediment has not to be changed. The parser for the hydrocarbon bacteria pathogens at the time of microbial consortium exists. Due to the complexity of the behavior of fine-grained sediments despite the many studies that have been performed, so far coherent and sufficient information regarding the hydraulic transmission of this kind of sediment do not exist. Different physical and chemical properties of the fluid and sediment and adhesion and aggregation properties, of cohesive sediments, cause different results in the researches (Pejrup and Mikkelsen 2010). Hence the investigation about the process of erosion of the fine-grain sediments input to reservoirs, to assess the flow of sediment transfer, hydraulic of viscous sediments, reservoirs sediment washing, design and operation of downstream irrigation network and so on have importance. On the same basis in this research, the process of erosion of fine-grained sediments within Karkheh dam reservoir, including erosion threshold shear stress, the rate of erosion, has been investigated using a circular flume.

Cohesive sediments after sedimentation in dam reservoirs, sedimentation ponds and canals, are gradually consolidated and for their hydraulic discharge it is necessary to know the velocity and shear stress of the erosion threshold of this type of sediment. To discharge the accumulated sediments behind the dam body, it is necessary to study the conditions of sediment erosion threshold and determine their erosion rate. In this research, the sediments of Karkheh dam reservoir have been studied and the erosion threshold of its sediments has been determined. A circular flume located in the laboratory was used and the tested sediments were prepared from behind the body of Karkheh dam. These sediments are fine-grained and before the main tests, the process of sedimentation and solidification of sediments in sedimentation columns for different periods of solidification (4, 16 and 35 days) were tested. Accordingly, sediments were prepared in circular flume and experiments were performed for different shear stresses. During the experiment, the trend of changes in erosion sediment concentration, shear stress, erosion threshold and erosion rate were evaluated. The results showed that the concentration of eroded sediments is a function of sediment consolidation time and bed shear stress. Came the results showed that the erosion rate is inversely related to the consolidation period, so that at the same shear stress, increasing the consolidation period reduces the erosion rate. The results showed that the shear stress of the erosion threshold of this type of sediments has a logarithmic relationship with the duration of their solidification. In addition, relationships were determined to determine the flow velocity at the erosion threshold in terms of specific gravity and sediment porosity ratio. Most ancient civilizations were formed to supply water and navigate rivers. Droughts and subsequent water shortages have led to the construction of dams and dams on rivers. Dams built along the river affect the characteristics of its flow and cause part of the sediment being transferred to settle in the reservoir of the dam. In general, sediments that move with water are divided into three parts: bed load, suspended load and washed load. The bed load is usually deposited at the beginning of the reservoirs due to its physical properties, but the fine-grained sediments move suspended below the dam body and then the sediment becomes a concentrated flow phenomenon. Thus, most of the sediments deposited behind the dam body are fine-grained and sticky, which should be taken into account when discharging sediments through the lower valves of the dam. Effective processes in the transport of fine-grained sediments include sedimentation, consolidation through controlled and careful studies, and erosion, which are mainly studied in the laboratory in flumes.

Material and methods

The study region

Karkheh dam with a height of 127 m located 22 km northwest of the city Andimeshk in Khuzestan Province, and on the Karkheh River. The dam Crest level with 234 m above sea level and a crest length of body size 3030 m, is the largest dam on Iran with a reservoir volume of 7.3 billion cubic meters, is the largest artificial lake in Iran with a length of 60 km. Karkheh watershed with geographical coordinates between 46° and 6 min to 49° and 10 min east latitude, 30° and 58 min and 34° and 56 min north latitude, is one of the great and important sub-basin of the country. This basin in terms of overall hydrological classification is a component of the Persian Gulf basin. From the north, this basin is near to the basin of the Sirvan, Ghezelozan, and Gharehchay Rivers, from the west to the river basin of the Iran-Iraq border, from the east to Dez River, and from the South limited to the western part of the border of the country. This watershed area in the territory of Iran is about 50,764 km^2 from which 42,175 km^2 is located on the upstream of Karkheh dam and 8589 km^2 downstream of the dam. From the whole, karate catchment area about the 27,645 km^2 of it is located in mountainous regions and about 23,119 km^2 of it is located in plain, which generally dominates the North and Southwards.

Sediments

Taking sediment samples using Garp on the four points located in the dam reservoir, downstream of the wire, the output of bottom gates and the back of the sediment withdrawal gate of the regulatory dam. Then the sediment samples were combined with each other and used for predetermined tests. The geographical location of gathered samples of sediments is visible in Fig. 1.

Liquidity and plasticity behaviors and their indices of the sediments from the above-mentioned location in the Karkheh dam were determined by doing the Atterberg limits

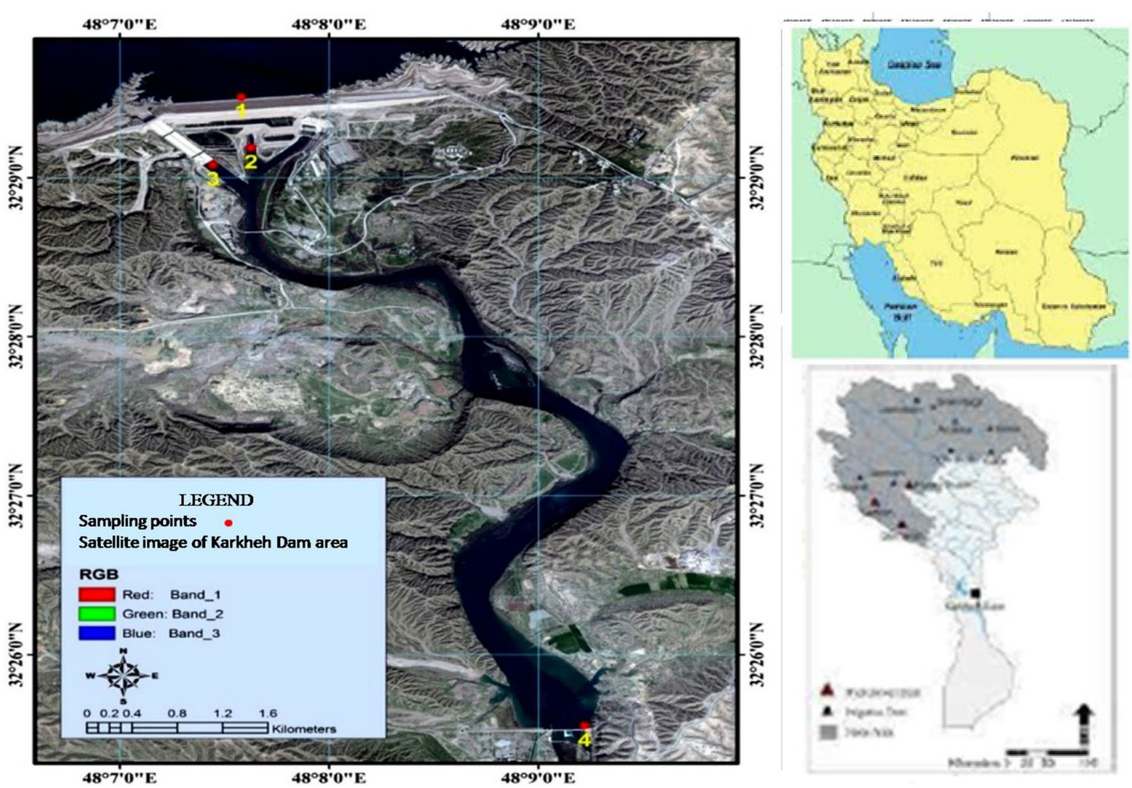

Fig.1 Geographical location of the study region

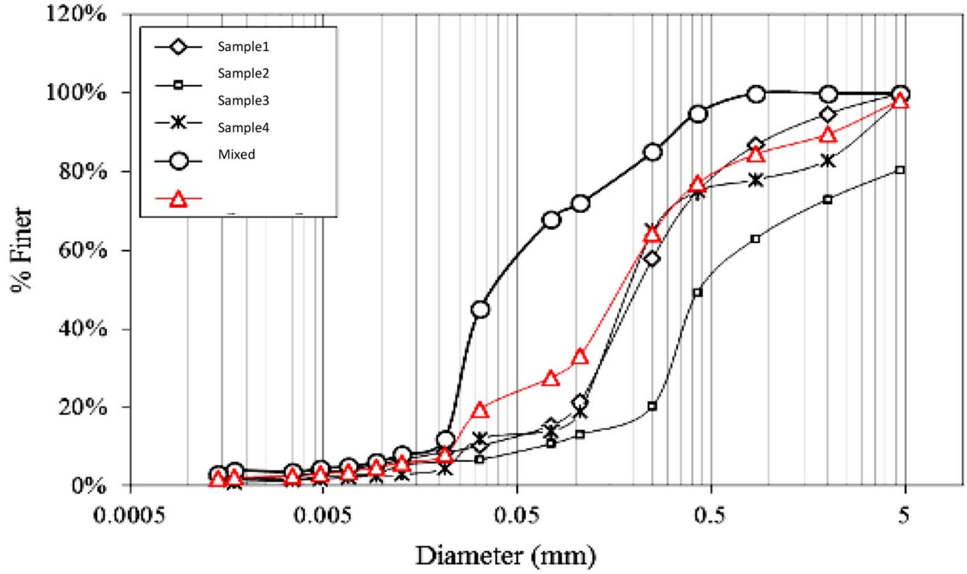

Fig. 2 The grain size distribution of Karkheh dam sediments

experiment and the results showed that these sediments have no Liquidation and plasticity behaviors. The classification of the sediments was determined to determine the grain size distribution by hydrometer test and the resulted grain distribution curve has been shown in Fig. 2.

Laboratory equipment's

To study the process of cohesive sediment erosion and sedimentation within the Karkheh dam reservoir, a circular flume located in the hydraulic laboratory of Shahrekord University was used. The internal, external and middle diameter of the flume were 1.3, 1.9 and 1.6 m, respectively, which is made from galvanized steel sheets and windows of Plexiglas. The cap of circular flume made of Plexiglas with a diameter of 1.6 m and is designed so that it fits inside the flume and it is 2 cm apart from the walls of the flume. Figure 3 shows cross section and dimensions of the flume. To measure the concentration of suspended material in the water column, 16 sampling valves were installed in four different positions at distances of 5.3, 10.5, 18.3 and 25 cm from the floor of the flume. Flume has two separate motors to rotate the flume and fitted cap. These motors give the ability to move the flume and its cap in clockwise or counterclockwise directions and

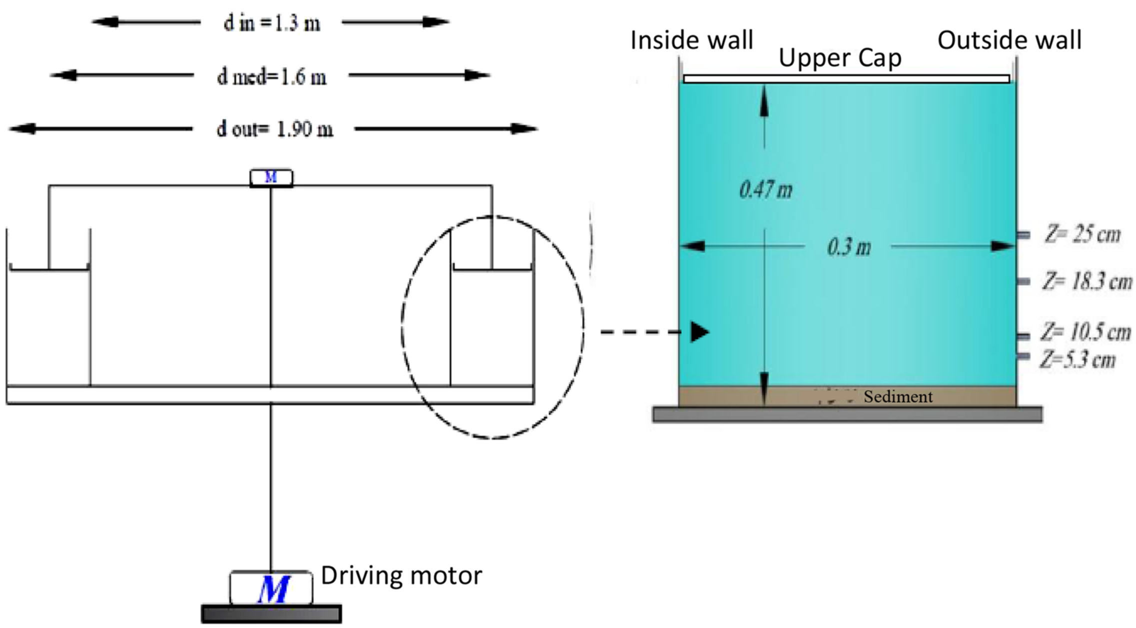

Fig. 3 Flume dimensions and cross section

Fig. 4 Different parts of the flume

for the contrary rotation to each other. Figure 4 shows different parts of the flume. In this research, using acoustic Doppler velocity meter (ADV) velocities were measured in three dimensions and five vertical cross-sections. The first cross-section was located 5 cm apart from the interior wall and the next sections were located toward the external wall, respectively. At each vertical section, four speeds were measured and the average speed of the flow for the area of the impact points was calculated using the weight average method. The researchers found that when the flume and cap rotate opposite to each other and the ratio of cap rotation speed to the flume rotation speed is 1:1; the velocity profile should be similar to the open-channel velocity profile and logarithmic. The researchers also showed that in this case the distribution of shear stress can be considered as uniform in the flume width and, therefore, the results obtained from a circular flume might be generalized for direct channels. Base on this research the relationship between average velocity and shear stress of flow with the sum of the flume and cap rotation speed can be described by the Eqs. (3) and (4):

$$V = 0.2085\ln(\omega) - 0.0556\,R^2 = 0.98, \tag{3}$$

$$\tau = 0.0254\omega^{1.1777} \quad R^2 = 0.99, \tag{4}$$

Table 1 Erosion threshold shear stress for sediments of Karkheh dam

30	14	3	Consolidation periods (days)
0.31	0.22	0.16	Erosion threshold shear stress (N/m^2)
0.21	0.18	0.15	Erosion threshold velocity (m/s)
0.15	0.13	0.11	Froude number

where: V is the average flow velocity m/s, τ is the flow shear stress N/m^2, ω is sum of the flume and cap rotation speed RPM.

Experiment's scheduling

To investigate the erosion threshold shear stress for the sediments of the Karkheh dam as Table 1, initially, it is necessary to examine the impact of consolidation and sediment depth. Therefore, some experiments with aims to find the depth and time of the sediments of consolidation were carried in cylindrical settling columns. As it is shown in Fig. 5 these cylindrical columns have equipped with sampling valves at 3 cm distance from each other and there is a region to regularly view the changes of the sediment depth. To do these experiments the sediments were mixed using an electric mixer and mixtures with different concentrations of

Fig. 5 Cylindrical settling columns

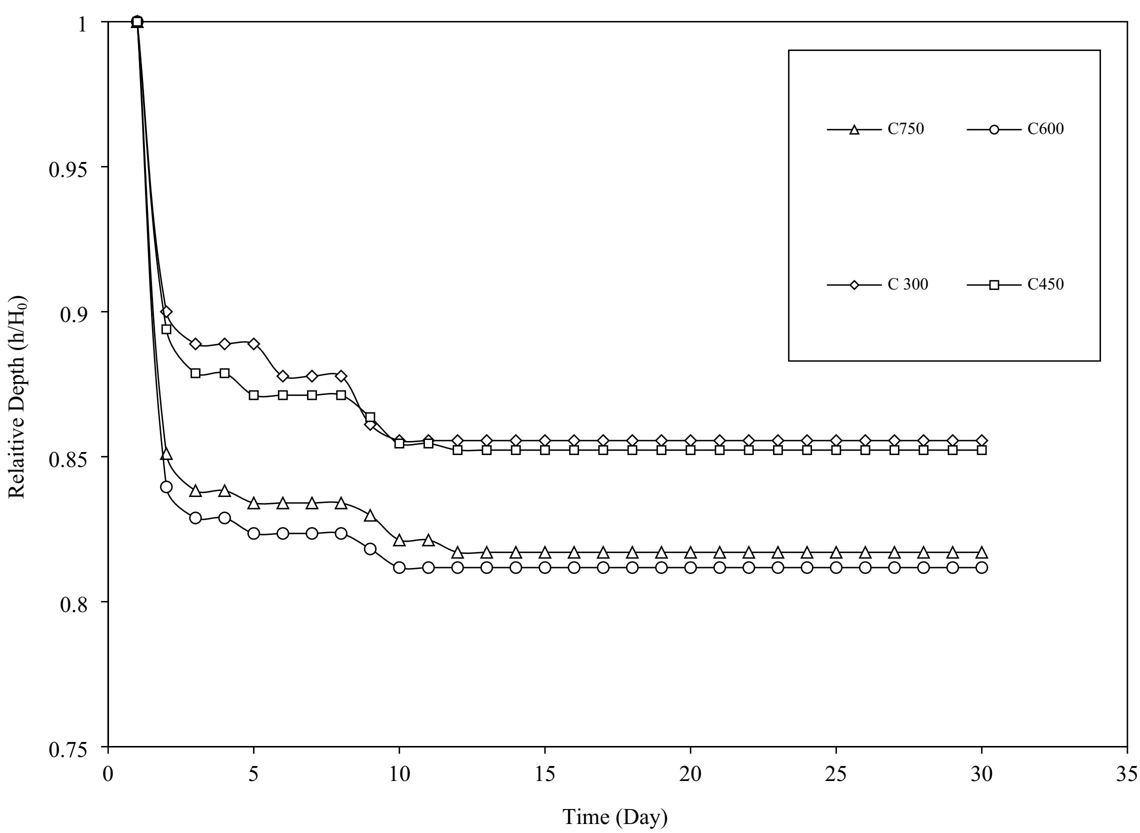

Fig. 6 The amount of daily sediment depth changes relative to the depth of the initial sediments for different concentrations in the consolidation test

sediment were prepared and these mixtures were poured into settling cylinders. The selected concentrations were 300, 450, 600 and 750 mg/l based around the sediment concentrations entering the Karkheh dam reservoir. To detect the changes of the settled sediments the depth of the sediments was measured daily for 30 days. Figure 6 shows the daily changes of the sediment depth relative to the initial sediment depth. As can be observed for concentrations of 300, 450, 600 and 750 mg/l, after 10, 12, 10, and 12 days the depth of the sediments remained unchanged, respectively. The results of these tests show that after 12-days sediment concentration and the depth of the settled sediments are not effective on the amount of consolidation. Concerning this issue to check the time of the consolidation on the erosion shear stress threshold, the time of the consolidation was chosen to be 3, 14 and 30 days. In the original tests after pouring the sediments in flume, to mix the sediments and smash the flocks flume and cap were rotated for 30 min with a total speed of 31 RPM (the speed of 14.8 rpm for the flume and 16.2 rpm for the cap) so that the caused shear stress was equal to 11.2 N/m^2. After thorough mixing of sediments, with keeping cap and flume motionless allow the sediments to settle while reaching the desired time for consolidation. According to the sediment settling column tests and the flume conditions both the depth of sediments and the depth of water on the top of sediments were considered to be 10 cm in circular flume tests. To determine the erosion threshold shear-stress and the erosion rate after elapsing the time for the consolidation process, the flume and cap were rotated against each other with the lowest speed and the ratio of 1:1. If the speed and the applied stress is less than erosion thresholds shear stress, the sediments remain unchanged in the flume bed, if it is more the sediment began to move and get suspended. In the latter case, the duration time to apply the target shear stress to reach a state of equilibrium by rotating the flume and the cap against each other, lasted and after this time the next rotating speed and shear stress and other stresses applied in the same way. Table 2 shows the hydraulic characteristics of the flow during the erosion test (Fig. 7).

In this research, the amount of eroded sediments from the stream bed with respect to the concentration of suspended sediments should be estimated at different times. Therefore, in each shear stress level in ten minutes intervals samples were taken from various depths and after the drying of samples in the Avon suspended sediment concentrations concerning the placement distance of sampling valves was calculated using of weighting method.

Table 2 Time and shear stress of flow in erosion tests

707–1105	395–705	245–395	60–245	0–60	Time (min)
9.5	7.4	5.8	4.1	2.5	Rotation speed of flume and cap (m/s)
1.4	0.9	0.58	0.31	0.13	Shear stress (N/m^2)
0.41	0.36	0.31	0.34	0.14	Velocity (m/s)
0.3	0.26	0.22	0.17	0.1	Froude number

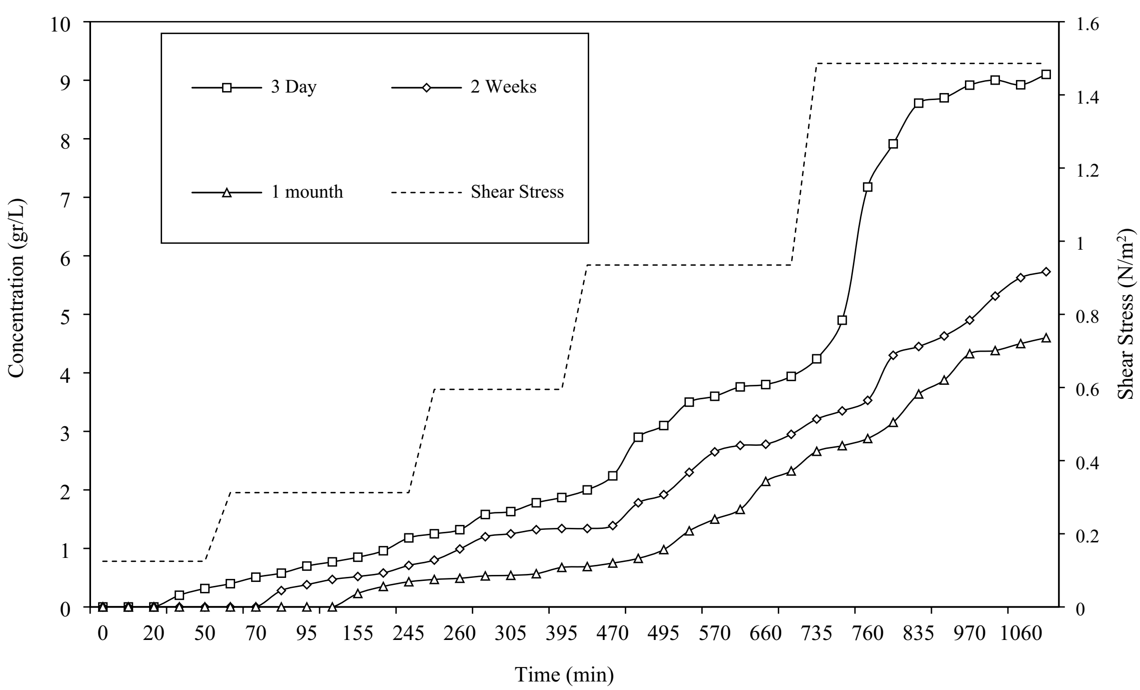

Fig. 7 Time variations of suspended sediment concentrations for different consolidation periods

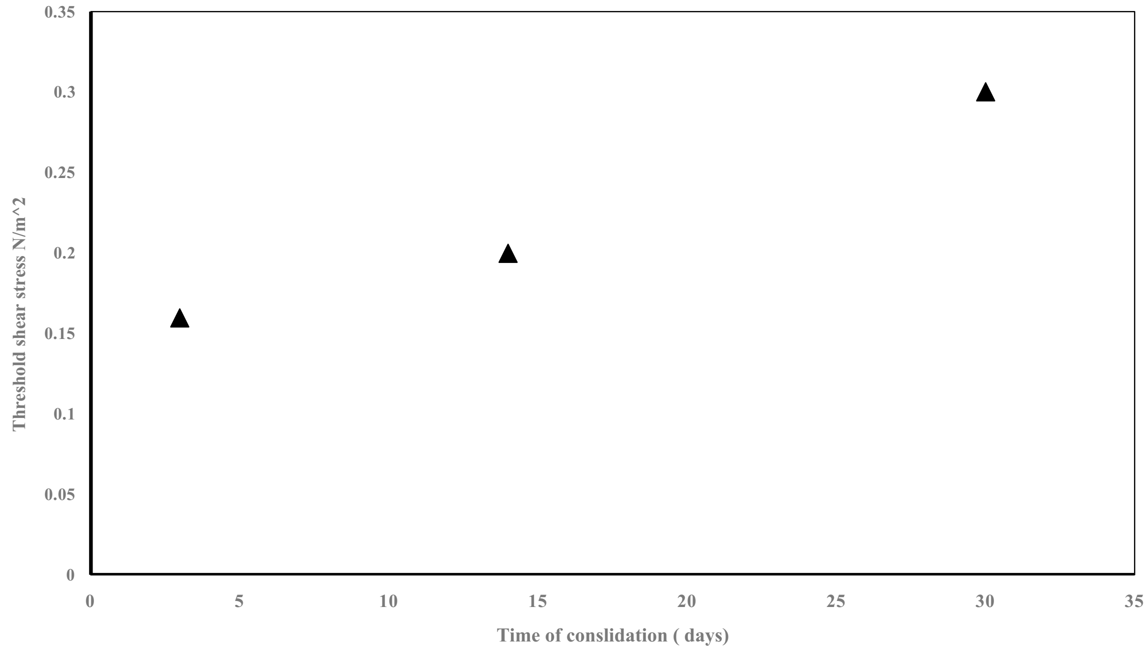

Fig. 8 The relationship between erosion threshold shear stress and time of consolidation

Results and discussions

Time variations of eroded sediment concentrations

To check the erosion rate and erosion threshold shear stress temporal changes of sediment concentration for different periods of consolidation time against the flow shear stress represent in Fig. 8. As can be seen in all the testes with increasing shear stress, the concentration of suspended sediments also increased. In other words, increase the shear stress increases the rate of erosion of the sediments of the bed. In the meantime, for a constant shear stress and specified time from the start of the test, by increasing the time of consolidation the concentration of suspended sediments for samples with different consolidation times decreases. For example, after 480 min of testing time in which the applied shear stress was calculated to be 0.9 N/m^2, the amount of suspended sediment concentrations for 3 days consolidated sediments were more than two weeks and a month consolidated sediment samples. It is also observed that the sediments with less consolidation period show more changes in response to increase the shear stress. The results showed under larger shear stress values the difference in the eroded sediments concentration rate in periods of 14 and 30 days is small but it is great for 3-day consolidated sediments. This situation is similar to the result got in the settling column tests, where no considerable difference between 14- and 30-days consolidated cases perceived. In addition, it is visible that the changes in the eroded sediments in this period of consolidation, follows a uniform and similar pattern but for the 3 days consolidation period at the shear stress of 0.9 N/m^2, a sudden increase in the concentration of eroded sediments occurred. This Circumstance can be caused by a change in the phenomenon of erosion. It may concluded that on the shear stresses less than 0.9 N/m^2 surface erosion should be dominated, but on the larger tensions the resistance of settled sediment grains is less than the power of the flow turbulence, which led to mass surface erosion of the bed. Surface erosion is the circumstance that individual

Table 3 Sediment components at the dissimilar places

Sampling points	Median size (mm)	Average size (mm)	Sorting coefficient	Skewness	Kurtosis
1#	0.017	0.030	1.552	0.079	0.859
2#	0.017	0.030	1.552	0.079	0.859
3#	0.017	0.030	1.552	0.079	0.859
4#	0.017	0.030	1.552	0.079	0.859
5#	0.017	0.030	1.552	0.079	0.859
6#	0.017	0.030	1.552	0.079	0.859
7#	0.017	0.030	1.552	0.079	0.859
8#	0.017	0.030	1.552	0.079	0.859
9#	0.017	0.030	1.552	0.079	0.859
10#	0.017	0.030	1.552	0.079	0.859
11#	0.017	0.030	1.552	0.079	0.859
12#	0.017	0.030	1.552	0.079	0.859
Average values	0.014	0.027	1.572	0.161	0.977

particles start to move from the bed of the cohesive sediment. Mass erosion should occur in greater quantities of shear stress (speed) and its characteristic is dislodging large sediment mass from the bed. Surface erosion has been addressed in other works such as Mehta (1991), Forsberg et al. (2018), Debnath and Chaudhuri (2010), Debnath et al. (2007) and so on. Some relationships about this subject have been provided as well (Table 3).

Erosion threshold shear stress

Estimation of erosion threshold shear stress has been done based on the increase in the concentration of suspended sediments. Concerning the time for consolidation and ample opportunity to sediment settling on the initial time of eroding experiments the concentration of suspended sediment was about 0.07 kg/m^3. Hence in this study with measuring the concentration of suspended sediments from the beginning of the eroding experiments shear stress in which was 0.1 kg/m^3, which is close to initial suspended sediments concentration at end of all consolidated periods was considered as an index of reaching the erosion threshold shear stress. Accordingly, the average of suspended sediment concentration, (C_s) for each shear stress (τ_b) was determined and between these values and flow shear stress for consolidation periods of 3–30 days relationships as provided in Eqs. (5), (6) and (7) were established:

$$C_s = 3.4805 \times \tau_b - 0.453 \quad R^2 = 0.94, \tag{5}$$

$$C_s = 3.2371 \times \tau_b - 0.611 \quad R^2 = 0.95, \tag{6}$$

$$C_s = 2.7098 \times \tau_b - 0.731 \quad R^2 = 0.93. \tag{7}$$

As statistical criteria (R^2) shows these relationships have acceptable accuracy to estimate the erosion threshold shear stress especially in sedimentary studies.

Moreover, concerning achieved results to estimate the erosion threshold shear stress of bed sediments based on the periods of the consolidation the Eq. (8) is obtained. The results of this relationship are provided in Fig. 9.

$$\tau_{ET} = 0.1516e^{0.0243\, C_T} \quad R^2 = 0.99, \tag{8}$$

Where:

τ_{ET} is erosion threshold shear stress N/m^2, C_τ is time periods the consolidation (days).

As it is evidence by increasing the time the consolidation of sediments, erosion threshold shear stress can also increase that these changes are as exponential relationship.

Erosion rate

To calculate the rate of erosion the relationship (9) was used. In this respect, the mass of eroded sediment resulting from the difference between two consecutive concentrations multiply by the volume of fluid. By dividing the mass of sediments by the time interval between two successive sampling on deposits to the area of flume bed, the average rate of erosion per unit time and unit area of flume bed can be determined:

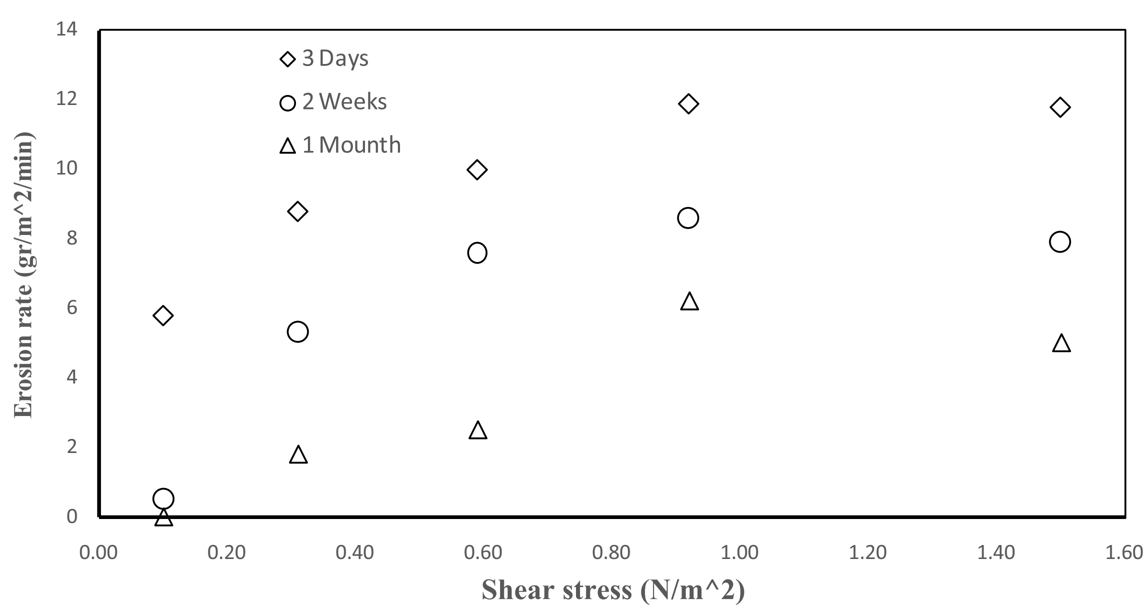

Fig. 9 The variations of erosion rate during different time period of consolidation

Fig. 10 Organization parameters of U-GEMS which is calculated to degree the erodibility of fine-grained sediments in a 10 cm core tube over a calibrated variety of shear pressures from 0.02–0.47 Pa (Dong et al. 2019)

$$Q_d = \frac{(C_2 - C_1) \times V_{\text{flume}}}{(t_2 - t_1) \times A}, \tag{9}$$

where: Q_d is the erosion rate gr/cm^2/min, $(C_2 - C_1)$ is different of suspended sediments concentration (g/l) during the two sampling times t_1 and t_2 (min), V_{flume} is the volume of the fluid within flume and A is the bed flume area m^2.

Based on the achieved results, the rate of erosion shear stress for each different consolidation period was calculated and presented in Fig. 10. According to Fig. 10, it can be stated that the rate of erosion has a reverse relationship with the consolidation period so that in the same shear stress, an increase of consolidation period will reduce the rate of erosion. The forces of cohesion in fine-grained sediments for a longer time of consolidation will create denser and tight sediment masses and result in more resistance to erosion. Also it is visible that for each of three periods of consolidation in shear stress III (0.59 N/m^2) the rate of steeling has reduced which this reduction is more observable in a one-month consolidation period. The reason for this matter can be explained by considering this fact that part of the eroded sediments should settled again and eventually affect erosion rates (Table 4).

Due to the limitation of the relationships provided to determine the erosion of cohesive sediments by researchers, a comprehensive relationship has been provided with respect to flow and sediment conditions. For this purpose, Hosseini's laboratory results were used for adhesive sediments in which

Table 4 Potential factors that may influence cohesive oil behavior (Kimiaghalam et al. 2014; Ostad-Ali-Askari et al. 2018, 2019, 2020a)

	Physical properties	Chemical properties	Mechanical and in-situ properties	Biological factors	Environmental factors
Soil	Grain size distribution Specific gravity Plasticity index	Mineralogy Organic content Gas content	Bulk density Shear strength Cohesion and friction angle	Different kinds of inhabitants in the soil structure or fluid such as effects of different plants, worms, crabs, and fish	Climate change, freeze and thaw, weathering
Eroding fluid and pore-water	Temperature	Mineralogy	Pore-water pressure		

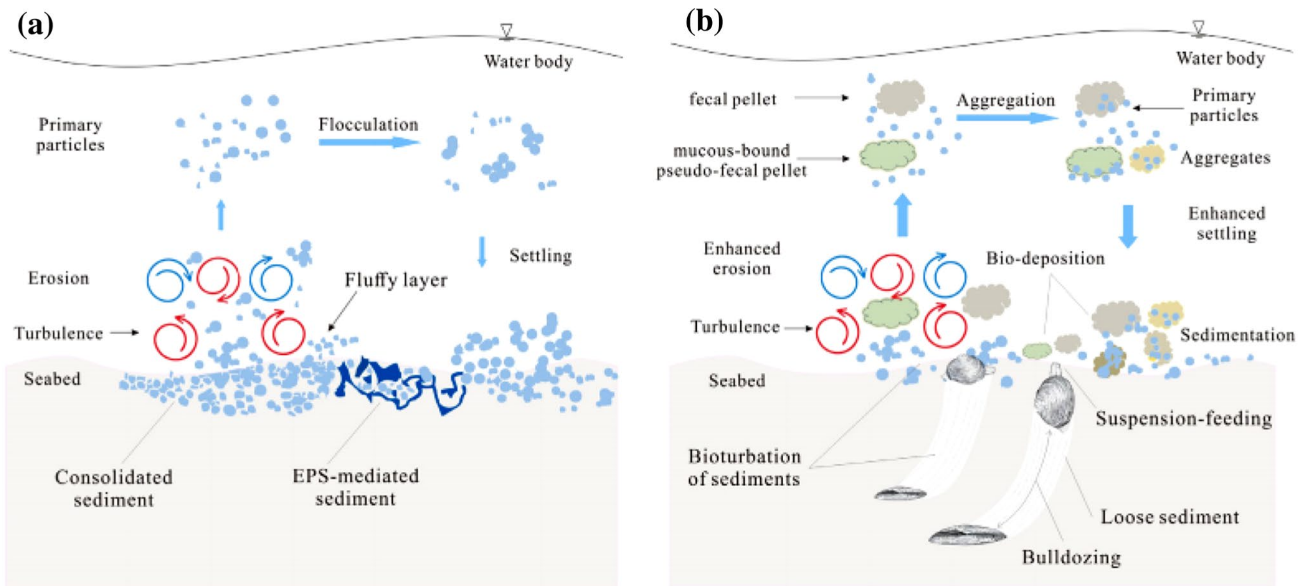

Fig. 11 Diagram figure of **a** sediment dynamics on a simple tidal flat modified from Maggi (2005), and **b** the organic mechanisms of tidal sediments and their effect on sediment erosion and deposition (Li et al. 2020)

parameters such as shear stress yield and sediment concentration were used. In the next step, using numerical solution of flow and sediment and using experimental results, constant coefficients for the relationship between erosion rate and shear stress function were determined. After validating the numerical model with the experimental data, then the experimental data were developed and then, with Buckingham theory, numerical numbers were obtained without regard to the effective parameters. The research showed that in cases where the number of laboratory data is not sufficient for statistical analysis, using new methods and with the help of calibration and validation tests, new information can be generated (Fig. 11).

Some of the parameters presented for the exponential relationship are flow-related parameters that can be calculated or measured. Parameters related to sediment properties are related to sediment concentration. This relationship is more simple in terms of extracting parameters related to sediments. Not much improve has yet been completed in considerating cohesive sediment erosion threshold owing to the characteristic physical, chemical and biological/biological difficulty of natural consistent sediments. Additional the examination of presence or absence of cohesive sediment erosion threshold, and dissimilar meanings of threshold has caused in difficulty in usage, clarifications and contrast of cohesive sediment threshold information. It was considered a appraisal on current practices and meanings applied for approximation of cohesive sediment erosion threshold; summarizes a variety of threshold shear stress attained by dissimilar detectives depend on field and workshop trials; and efforts to report the disagreement concerning the presence of cohesive sediment erosion threshold. Additional, the investigation similarly was displayed the requirement of cohesive sediment erosion threshold on cohesive sediment belongings.

Conclusions

Experimental studies for sediment erosion of the Karkheh dam were carried out using a circular flume. Bed shear stress and the consolidation period of the factors influencing the rate of erosion of the sediments, so that for a certain shear stress the consolidation period, determines the amount of erosion. The erosion rate during a short period of consolidation is vaster. The results showed that in shear stress greater than 0.9 N/m^2 the erosion process, of the 3-day consolidated sediments changes from surface mode to the mass erosion mode. In this Research the erosion threshold shear stress for the 3, 14 and 30 days consolidation period was estimated to be 0.16, 0.18 and 0.31 N/m^2, respectively. Additionally the relationship between sediment consolidation period of the Karkheh dam and erosion threshold shear stress provided. The results of the erosion rate suggest an inverse relationship between this parameter and the life of the settled sediments. Based on the above-mentioned results the best flow shear stress for sediment removal by flashing from the Karkheh dam reservoir should be greater than 0.31 N/m^2. The obtained information can be used in the reservoir management to concentrated sediment passage, for washing the reservoir as well as management of downstream transmission and distribution network.

Using the concept of quasi-fluid model and combining it with the equations of bed shear stress and flow resistance in canals containing vegetation and probabilistic modeling approach, a model for transferring sediment bed load in canals and waterways containing vegetation is presented. The developed model is based on a new definition of dimensionless parameters of flow intensity and bed load intensity in terms of vegetation characteristics, in addition to flow characteristics and sediments. Combining quasi-fluid conceptual model with substrate load transfer mechanisms for optimal accuracy in modeling provides bed load transfer in canals containing vegetation. Also, parametric analysis of vegetation effects on barbed wire values was performed in the field of erosion and transfer of sediments around the vegetation and obstacles in the flow path. Comparison of the results of the developed quasi-fluid model showed that despite the use of dimensionless parameters in barbell relationships, the accuracy of the quasi-fluid model is better than both the initial relationship and the calibrated results of these relationships. Considering the favorable results of the quasi-fluid approach in simulating the transfer of bedload sediments through the vegetation, the proposed approach can be developed in other studies related to sediment and river engineering and the limitations of research on the transfer of bedload from the vegetation in the bed. And raised the body of canals and rivers. The sedimentation process of fine-grained and coarse-grained sediments is completely different. In non-cohesive sediments, erosion and sedimentation occur simultaneously when the flow shear stress is greater than the critical shear stress at the point where the particles move. In permanent conditions, when the tension. The bed is equal to the critical shear stress, the rate of sedimentation and erosion is equal. However, erosion and deposition for cohesive sediments at any shear stress cannot occur simultaneously. This is because when cohesive particles settle, processes Electrochemical and biological bind these particles to the substrate. Therefore, a greater shear stress is required to retransmit these particles than when they have settled, because in addition to overcoming the mass of the particles to be transferred and suspend again, it must also overcome the adhesion force. For this reason, cohesive sediments have two separate critical shear stresses, one for deposition and the other for erosion. Based on this, two types of complete and partial sedimentation are defined for cohesive sediment. When the shear stress of the bed is less than the critical shear stress, complete settling occurs and all sediment particles and masses settle.

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Author contributions All authors designed the study, collected data, wrote the manuscript and revised it.

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Availability of data and materials Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

Declarations

Conflict of interest There is no competing of interest.

Ethical approval The present Study and ethical aspect was approved by Water Engineering Department, College of Agriculture, Shahrekord University, Shahrekord, postal code 8818634141, Iran.

Consent to participate All authors designed the study, collected data, wrote the manuscript and revised it.

Consent to publish All authors agree to publish this manuscript. There is no conflict of interest.

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