Scientia Iranica A (2021) 28(6), 3072–3081

Sharif University of Technology
**Scientia Iranica**
*Transactions A: Civil Engineering*
http://scientiairanica.sharif.edu

# Experimental study of the consolidation of the cohesive sediments
# Case study: Karkheh dam reservoir

**M. Goudarzi, B. Lashkar-Ara*, and H. Seyed Kaboli**

*Department of Civil Engineering, Jundi-Shapur University of Technology, Dezful, Postal Code: 64616-18674, Iran.*

Received 4 November 2020; received in revised form 4 February 2021; accepted 13 September 2021

**KEYWORDS**
Consolidation;
Cohesive sediments;
Settlement column;
Deposition;
Dam reservoir.

**Abstract.** Changes in cohesive sediment density due to consolidation can cause significant changes in dam foundation stress and reservoir site permeability. The consolidation process in the Karkheh dam reservoir was investigated in this study using a settling column and varying the initial sediment concentration from 50 to 150 gr/lit. The initial sediment concentration, initial settlement height, and temperature are effective parameters for settling cohesive sediments. In addition, the effects of the bed elevation of the reservoir, as well as the scale effects on the settlement of cohesive sediments, were also studied. The results showed that the initial free settlement process and the hindered settlement phase take more time than self-weight consolidation settlement stages by increasing initial sediment concentration. Therefore, at an initial sediment concentration of 25 g/l and 150 g/l, the samples began self-weight consolidation after 1.5 h and 17.5 h respectively. The results also showed that the final average concentration increased linearly with the initial concentration. The concentration of the settled sediments decreased with the initial height in a non-linear trend. In addition, under the same initial conditions, by increasing the diameter of the settlement column, the final concentration of the settled sediments first decreased and then increased.



## 1. Introduction

Considerable changes in the dry density of cohesive sediments that settle and accumulate in the dam reservoir over time can significantly change the original design and functionality of the dams and hence, should be specifically studied. Behind the body of large dams, the shear stress field range is affected, especially in local areas [1]. It is challenging to remove consolidated sediments, which can significantly decrease the useful storage capacity of the dams and cause many problems for power plants machinery as well as irrigation network equipment [2–5]. The distribution of boundary shear stress has an influence on the rate of erosion and sedimentation [6]. When investigating sediment transport and bathymetry changes, knowledge of boundary shear stress is essential [7]. The creation of depth-dependent critical shear stress for erosion, $\tau_{cr} = \tau_{cr}(z)$, where $z$ is the distance from the water-sediment interface down into the bed, is one of the consequences of the bed consolidation process [8–10]. In arid and semi-arid areas, fine particles are transported to dam reservoirs by rivers. The particles diameter becomes smaller as they approach the dam body due to the flow sorting mechanism in the reservoirs. Cohesive

*. *Corresponding author.*
*E-mail addresses: masoud.goodarzi69@gmail.com (M. Goudarzi); Lashkarara@jsu.ac.ir (B. Lashkar-Ara); hkaboli@jsu.ac.ir (H. Seyed Kaboli)*

doi: 10.24200/sci.2021.57114.5069

sediments with very fine particles show more micromechanical properties. In several experiments, the behavior and interaction of these sediment particles are observed. The contact surface of cohesive sediments is greater than their mass, causing the high cation exchange capacity of these particles [11]. The presence of cation and anion particles in fine-grained sediments, along with their cohesive properties, causes smaller particles to collide with each other and form larger masses, called flocculation. Flocculation is the accumulation of smaller particles to turn into a larger particle (floc) that affects the particle size distribution in the water column [12]. The flocculation rate depends on the flow shear stress, the particle concentration, the falling velocity, the salinity, the dissolved ions, the temperature, and the biological processes [13]. Because of their flocculation properties, the behavior of cohesive sediments is very complex, and several experiments have been conducted to classify and clarify the behavior of these sediment types [14]. Cohesive sediment flocculation is of particular importance because it is a key process that impacts other processes of sediment transport, such as settlement, resuspension, consolidation, and entrainment [15]. These processes are relevant for the evaluation of morpho-dynamic evolution in estuaries and coastal areas, as well as for sediment control and coastal engineering applications, such as waterway dredging maintenance and mudflat reclamation [16,17].

The settlement process of fine and coarse sediments is quite different. In non-cohesive sediments, when the shear stress of the flow is greater than the critical shear stress (the threshold at which the particle starts moving), scouring and settlement occur simultaneously. In steady flow conditions, when the bed shear stress is equal to the critical shear stress, the settlement and erosion rates are identical. However, scouring and settlement of the cohesive sediment cannot occur simultaneously at any shear stress. This is attributed to the fact that when the cohesive particles settle, the electrochemical and biological processes bond these particles to the bed surface [11]. Therefore, to transcend the cohesive force and the mass of the particles, more significant shear stress is required to re-transfer these particles. For this reason, cohesive sediments have two different critical shear stresses for the settlement and scouring [12].

For many coastal engineers, the appearance of fluid mud is a nuisance because it can create numerous technical problems [18]. Understanding the production, transport and subsequent fate of fluid mud is very important [19].

Khastar-Boroujeni et al. [11] studied the effect of treated urban wastewater on the settlement of cohesive sediments. They indicated that wastewater increased the settlement of sediments by 30% on average and different percentages of wastewater had almost the same effect on settlement. Taheri et al. [20] experimentally studied the effect of consolidation time on the scouring of cohesive sediments. They indicated that the scouring of sediments is a function of consolidation time and bed shear stress. Furthermore, during the consolidation period (one day), surface scouring developed into mass scouring through a relative rise in the shear stress. However, surface scouring occurred in other consolidation periods for all shear stresses. Tan and Chen [1] analyzed the physical and chemical characteristics of cohesive sediments, and the consolidation mechanism of the cohesive and non-cohesive sediment samples, using an experimental flume. They indicated that the dry density of sediments increased significantly in the initial stage of consolidation (approximately 65% of the total), but in the long-term consolidation trend, it slowly increased in the next stage. Considering the state of the sediment particles during the settlement process, sediment settlement can be divided into three stages: The initial free settlement, hindered settlement, and self-weight consolidation settlement [21].

Xu et al. [22] studied how the flocculation process affects the formation, sedimentation, vertical structure, and eventually the fluid mud layer process of entrainment. Due to long-term sedimentation, the dry density of the cohesive sediment accumulated in the lake undergoes considerable changes, which could change the original dam design and function. For example, by consolidating the natural bedding, which consists of cohesive sediments, the seepage field in a dam foundation is significantly altered. The specific discharge of suspended and bed sediment is 8089.77 and 21.84 tons/year/km$^2$ respectively in the catchment area of Karkheh Dam. Because of different consolidation conditions in reservoirs, the consolidation theories used in the past could not be applicable for a particular reservoir. In addition, since Karkheh Dam is an embankment dam, the effect of cohesive sediments on seepage in the dam foundation should be considered, and the results of this study can be of great help in studying the seepage of Karkheh Dam foundation. The density change of cohesive sediments is more important than the density change of coarse sediments, especially in the initial consolidation stage. Therefore, the aim of the present study was to determine changes in dry density in the initial consolidation stage by analyzing the indirect interactions between sediment particles.

## 2. Materials and methods

### *2.1. Study area*

Karkheh Dam, with a height of 127 m from the foundation, is located 22 km northwest of Andimeshk in Khuzestan province. It is built on Karkheh River. Karkheh Dam is the largest dam in the history of Iran, with a crest height of 234 m above sea level and a crest length of 3030 m, with a reservoir capacity of 7 billion and 300 million cubic meters. These features have made this dam the largest dam in Iran which has the largest artificial lake with a length of 60 km. Karkheh catchment, with an eastern longitude of 46° and 6′ to 49° and 10′ and northern latitude of 30° and 58′ to 34° and 56′, is considered one of the largest and most important sub-basins of Iran. Considering general hydrological distribution, the Karkheh basin is part of the Persian Gulf basin. The basin of Kharkheh is bounded to the north by the rivers Sirvan, Ghezel Ozan, and Qara-Chay, and to the west by the catchment area of the Iran-Iraq border rivers, and to the east by Dez River, and to the south by the western Iran-Iraq border. The basin area is approximately 50764 km$^2$, of which 42175 and 8589 km$^2$ respectively are located upstream and downstream of Karkheh Dam. Figure 1(a) shows the Karkheh basin, which could be categorized into two different regions because of geographical factors. The northern part of the basin area, which is approximately 27645 km$^2$, is located in mountainous areas, and the southern part is approximately 23119 km$^2$.

In this study, a bathymetric map was prepared with the objective of determining the water depth of Karkheh Dam Lake. This map was prepared to investigate the impact of the scale of water depth and the effect of coastal bay walls on the process of sedimentation and consolidation. For this purpose, the Karkheh Lake Bathymetric DEM shaded relief image was prepared using point depth measurement data that record by the Khuzestan Water and Power Authority. The result is shown in Figure 1(b).

### *2.2. Sediments*

Seven different locations have been determined for sediment sampling based on the surveys conducted on Karkheh Dam reservoir. The location of samples and the coordinates of the seven sampling stations are shown in Table 1. The standard Van Veen Grab Sampler was used to collect bottom sediment samplers (Figure 2). Weights were added to the sampler in order to sample at a depth of more than 30 m. In the collected sediment sample, the minimum weight was 1.5 kg, which was a wet weight. A subsample of 1 to 1.5 kg was taken in cases where a larger sample was collected. Samples were labeled and stored in a sealed bag after sampling for further analysis to determine the physical and chemical characteristics. To reduce the impact of reservoir depth on the grain size distribution of sediments deposited in Karkheh Dam reservoir, all sediment samples were mixed together.

**Table 1.** Coordinates of the sampling stations.

| Sample number | Longitude | latitude | Depth of water (m) |
|---|---|---|---|
| S1 | 3600552 | 228840 | 30 |
| S2 | 3600720 | 228844 | 35 |
| S3 | 3602443 | 227092 | 30 |
| S4 | 3599234 | 228888 | 55 |
| S5 | 3599222 | 229717 | 60 |
| S6 | 3599193 | 229596 | 65 |
| S7 | 3601127 | 228835 | 40 |

**Table 2.** Physical properties of the sediments of Karkheh Dam reservoir.

| Sand (%) | Clay (%) | Silt (%) | LL[a] | PL[b] | Gs[c] |
|---|---|---|---|---|---|
| 11 | 41 | 48 | 37.7 | 18.2 | 2.65 |

[a]: Liquid Limit; [b]: Plastic Limit; and
[c]: Specific gravity of sediments

The results are seen in Tables 2 and 3. Using the Mastersizer, the sediment size distribution was determined. Figure 3 shows the gradation results for each sample.

### *2.3. Experimental setup*

A plexiglas settlement column with an inner diameter of 15 cm and a height of 50 cm was used for investigation in the current research. The device was developed at the hydraulic laboratory of Jundi-Shapur University of Technology, Dezful, Iran. To measure the pore water pressure during consolidation, ten piezometers were installed on the plexiglas wall from 1 cm above the column floor with 1 cm spacing, and piezometers were placed on the board plate by plastic pipes to read the pressure at any given time. Figure 4 illustrates some of the models used in the experiments. The reservoir of Karkheh Dam has varying depths in the natural state and has different cross-sections, as seen in Figure 1(b). Therefore, the results can be affected on a scale by various locations of the reservoir. Therefore, multiple sediment columns with different diameters were used to study the impact of the sediment column scale on sedimentation and consolidation processes.

### *2.4. Experimental procedure*

During the initial free settlement stage, which is related to the start of the settlement process, sediment particles are completely scattered due to different settlement rates, as shown in Figure 5(a). Then, the aggregates (gravel and sand particles) settle on the bed floor with a higher settlement rate. In the meanwhile, under the action of electrostatic force, the clay particles overlap each other to form a simple flocculent structure, and the interface appears [21]. As settlement continues, the distance between the floc structures decreases, and the floc structures overlap to form the flocculation frames, and settlement enters the hindered settlement stage (Figure 5(b)).

At this stage, the effective stress between the floc structure appears and develops at a relatively small speed, and the excess pore pressure begins to dissipate

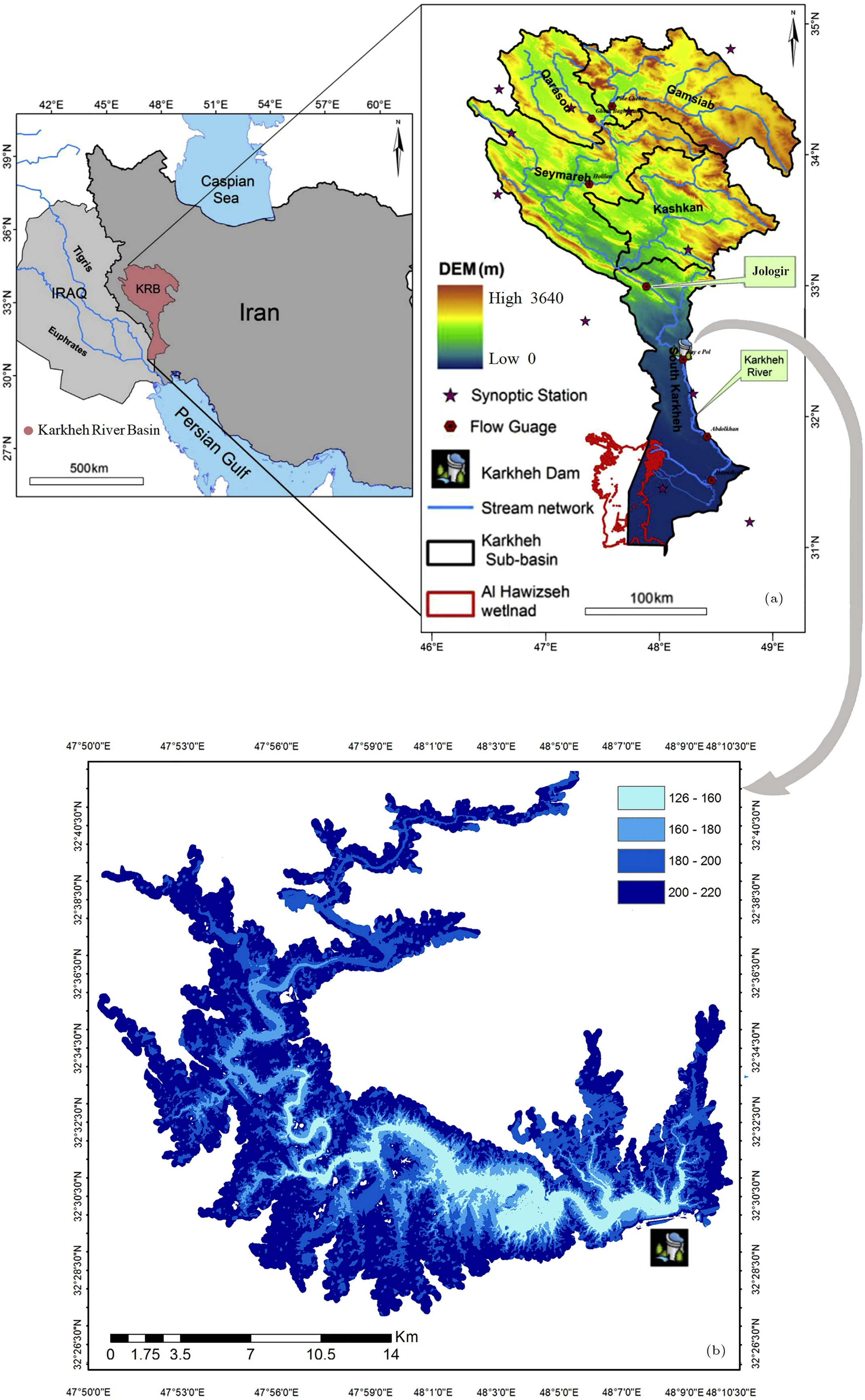


**Figure 1.** (a) Location of Karkheh River catchment in Iran. (b) Lake Bathymetry of Karkheh Dam reservoir.

**Figure 2.** Bottom sediment sample collection from Karkheh Dam lake.

**Table 3.** Chemical properties of the sediments of Karkheh Dam reservoir.

| EC[a] | PH[b] | Anions | | | Total anions | Cations | | | | Total cations | SAR[e] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $HCO_3^-$ [c] | $Cl^-$ | $SO_4^{2-}$ [d] | | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ | $K^+$ | | |
| 1.6 | 7.34 | 5 | 6 | 15 | 26 | 11.5 | 4 | 4.92 | 5.72 | 26.14 | 1.25 |

Note: [a]: Electrical Conductivity; [b]: Potential of Hydrogen; [c]: Bicarbonate; [d]: Sulfur; and [e]: Sodium Adsorption Ratio.

from its maximum value. Settlement curves at this stage are linear on logarithmic scales.

Meanwhile, pore water in the middle and lower layers flows along the internal seepage channel under the hydraulic gradient, which could destroy the floc frames. In the self-weight consolidation settlement stage, effective stress is developed under the weight of settled sediments, which intensifies the compression of the floc frames, as shown in Figure 5(c).

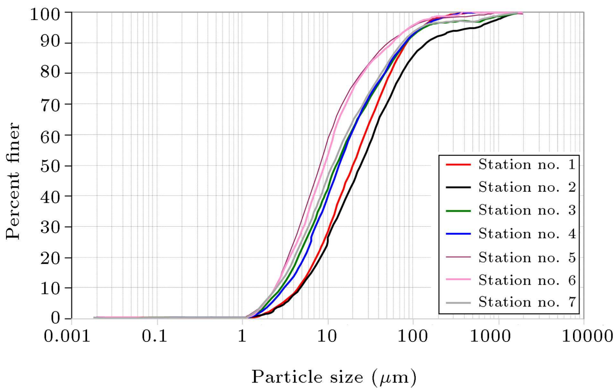


**Figure 3.** Gradation curve of the tested sediment samples.

As mentioned before, the main purpose of the present study was to evaluate the different stages of settlement and consolidation of cohesive sediments of Karkheh Embankment Dam.

In this respect, various scenarios have been developed considering the concentration of sediments entering Karkheh Dam reservoir. To assess the effect of initial concentration, initial height, cross-section, and temperature on the settlement and consolidation of cohesive sediments, these scenarios were described to determine porosity and changes in water pressure over 45 days.

Considering the temporal changes in the concen-

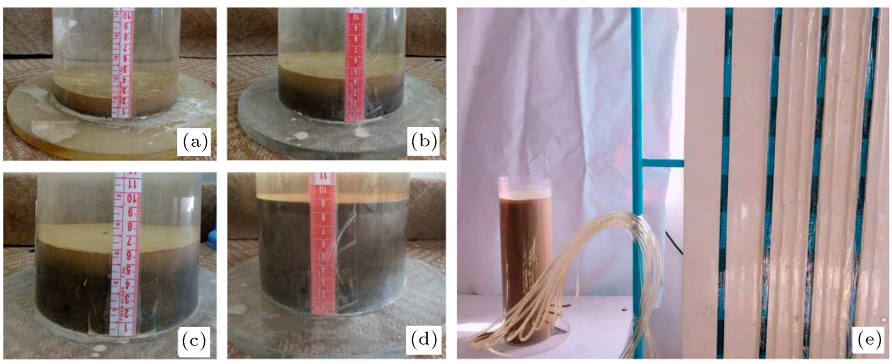


**Figure 4.** Recording the surface height of the water-sediment interface through settlement columns at different concentrations: (a) $C_0 = 25$ gr/lit, (b) $C_0 = 50$ gr/lit, (c) $C_0 = 75$ gr/lit, (d) $C_0 = 150$ gr/lit, and (e) cylinder of sedimentation to monitor changes in pore water pressure.

**Table 4.** Conditions for carrying out experiments on multiple samples.

| Test no. | $T_t$[a] (days) | $H_1$[b] (cm) | $D$[c] (cm) | $C_0$[d] (gr/lit) | $T$[e] (°C) | Description/consideration |
|---|---|---|---|---|---|---|
| 1 | 45 | 50 | 15 | 50 | 22-24 | Measurements: Initial consideration, record of interface level |
| 2 | 45 | 50 | 15 | 75 | 22–24 | |
| 3 | 45 | 50 | 15 | 100 | 22–24 | |
| 4 | 45 | 50 | 15 | 125 | 22–24 | |
| 5 | 45 | 50 | 15 | 150 | 22–24 | |
| 6 | 2–45 | 10 | 15 | 100 | 22–24 | |
| 7 | 2–45 | 20 | 15 | 100 | 22–24 | |
| 8 | 2–45 | 30 | 15 | 100 | 22–24 | |
| 9 | 2–45 | 40 | 15 | 100 | 22–24 | |
| 10 | 2–45 | 50 | 15 | 100 | 22–24 | |
| 11 | 2–45 | 20 | 4 | 200 | 22–24 | Measurements: Final consideration |
| 12 | 2–45 | 20 | 6 | 200 | 22–24 | |
| 13 | 2–45 | 20 | 10 | 200 | 22–24 | |
| 14 | 2–45 | 20 | 14 | 200 | 22–24 | |
| 15 | 2–45 | 20 | 38 | 200 | 22–24 | |
| 16 | 45 | 50 | 15 | 50 | 6 | Measurements: Record of interface level |
| 17 | 45 | 50 | 15 | 50 | 24 | |
| 18 | 45 | 50 | 15 | 100 | 6 | |
| 19 | 45 | 50 | 15 | 100 | 24 | |

Note. [a]Time; [b]Initial sediment-water interface height; [c]Diameter of column; [d]Initial concentration; and [e]Temperature.

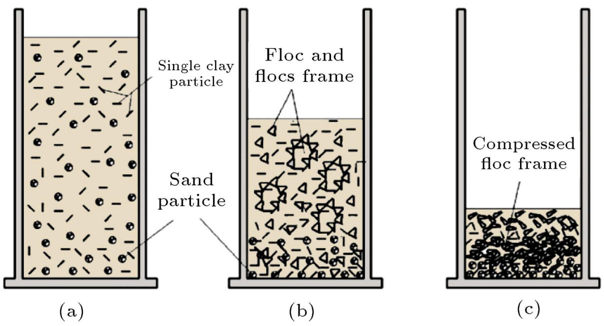


**Figure 5.** Sediment particles state in the suspension of settled cohesive sediments and consolidation process (Baotian et al. (2013)).

tration of sediments input to the reservoir, the annual sediment-yield curves of the dam reservoir were used as the initial sediment concentration scenario. According to the curve analysis, at the Jologir (Mazhin) hydrological station, the maximum concentration of sediments input to Karkheh Dam reservoir was estimated to be 125 g/l. The location of the Jologir (Mazhin) hygrometry station is shown in Figure 1(a). As it mixes with the water in the reservoir on the path leading to the dam outlet, the concentrations of sediment in the inlet of the reservoir decrease from their initial value. However, input sediment concentrations of 50, 75, 100, 125, and 150 g/l were chosen for the analysis of deposited sediment settling and consolidation mechanisms in accordance with the flow conditions at Karkheh Dam reservoir. In addition, the impact of the initial height on the settlement and consolidation of cohesive sediments was tested with a constant sediment concentration of 100 g/l at various heights of the Plexiglas column, taking into consideration the variations in the elevation of different reservoir bed points. Furthermore, considering the natural changes in the cross-sectional area of the reservoir in different points and consequently, its effect on the settlement of cohesive sediments, to study the scale effect, changes in the initial height of the water-sediment mixture, and the cross-section of the tested samples, settlement columns with different diameters were used. The effects of natural changes in the water temperature in the dam reservoir on the settlement of cohesive sediments were also studied considering hot and cold temperatures.

In all experiments, changes in water-sediment height, pore water pressure, and porosity of the settled sediments were measured and recorded. Experiments with different conditions were conducted to study the effect of various parameters such as initial concentration, initial height, temperature, and scale on settlement and consolidation prediction, and the results are presented in Table 4.

## 3. Results and discussion

### *3.1. Effect of the initial concentration*

One of the effective parameters in the settlement and consolidation processes is the initial concentration of the water-sediment mixture. Experiments with five different initial concentrations of 50, 75, 100, 125, and 150 g/l were conducted using a settlement column to research this parameter. Figure 6 indicates temporal variations in the relative sediment-water height

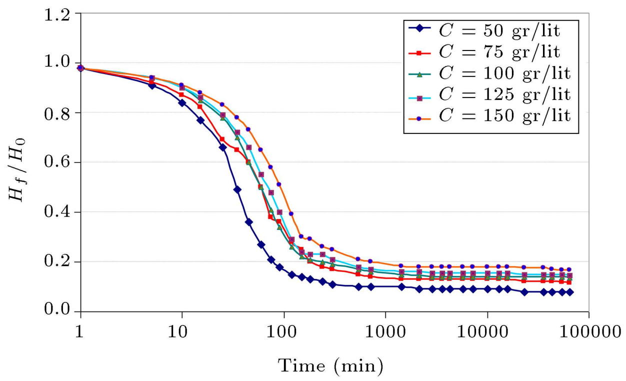


**Figure 6.** Temporal changes of $H_f/H_0$.

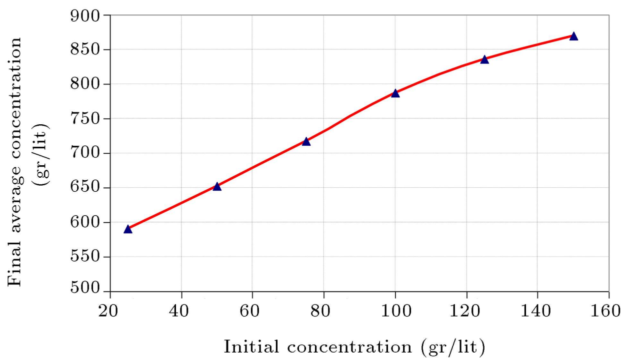


**Figure 7.** Changes in the final average concentration in the initial concentration scenario.

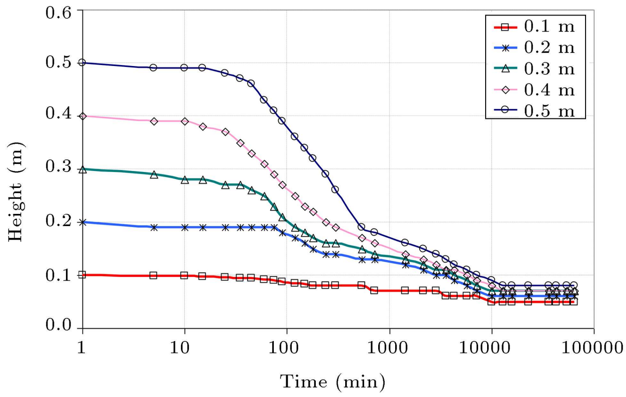


**Figure 8.** Experimental results of the initial height scenario.

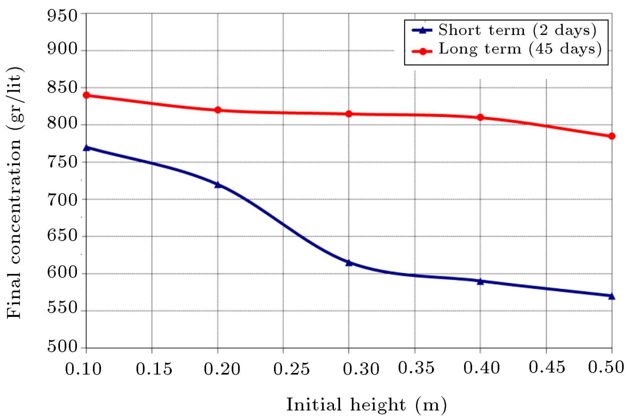


**Figure 9.** Changes in the final sediment concentration versus initial heights.

($H_f/H_0$) for various initial sediment concentrations. Figure 7 also shows variations in the final average concentration of the samples compared to the initial concentration.

Temporal changes of $H_f/H_0$ showed that by increasing the initial concentration of sediments, the $H_f/H_0$ curve lay higher than that of lower concentrations.

However, based on the result shown in Figure 6, the temporal change in the gradient of this curve was almost the same for all initial concentration scenarios. Observations also showed that in all cases, complete consolidation occurred after 35 days, and there was a steady settling velocity during the initial free settlement stage. As can be seen from Figure 7, the final average concentration increased linearly with the initial concentration. In addition, the settled sediment load can significantly improve the final consolidation, and the time to reach a stable consolidation state is much longer.

### 3.2. *Effect of the initial height*

Experiments with the same initial concentration of 100 g/l and varying initial heights were conducted to study the effect of the initial height on the settlement and consolidation processes. As can be seen from Figure 8, with the initial height, the concentration of settled sediments decreased with a nonlinear trend. Furthermore, changes in the final sediment concentration at various initial heights in the short-term (2-day) and long-term (45-day) periods have been studied and the results are shown in Figure 9. The results showed that during the short-term settlement period, with the increase of the initial height of the sediment, the change of the sediment concentration is relatively reduced, which determines the initial free settlement stage. This is attributed to the fully developed flocculation of clay particles and the appearance of a flocculated structure during the initial free-settling stage.

The sediment concentration begins to decrease from the water surface to the column bottom as the particles in the upper flow region start to settle. Due to the flocculation structure of the cohesive sediment particles, the settling process is faster than a single particle. However, the flocculation structure is significantly compressed under the weight load of deposited sediment, which is why the average concentration of settled sediments decreases in the short-term settlement period.

The downward trend of the average concentration is only significant in the short term. The average concentration at the initial sedimentation height of 0.5 m in the 45-day long period was almost the same as the average concentration at the initial sedimentation height of 0.1 m, as shown in Figure 9. Figure 9 also shows that the net frame of the flocculation structure is fully compressed and consolidated.

### 3.3. Effects of the scale

Since the sedimentation in some parts of the dam reservoir is affected by the coastal wall, the impact of sediment column diameter was investigated in this study. The diameter of the settlement column significantly affects the settlement of the suspended cohesive sediments and the consolidation behavior of such sediments, which is attributed to the effects of the wall (vertical convection) the interactions, and the clay particle flocculation.

The settlement column diameter significantly affects the settlement of the suspended cohesive sediments and the consolidation behavior of such sediments, due to the effects of the wall, the interactions (vertical convection), and the flocculation of the clay particles.

For this reason, previous studies have reported different sediment settlement rates in settlement columns with different diameters and the same sediments.

For this purpose, experiments were performed in short-term and long-term periods in settlement columns with diameters of 4, 6, 10, 14, and 38 cm considering an initial concentration of 200 g/l with an initial height of 20 cm for two times periods of 2 and 45 days. Figure 10 shows the scenario of settlement column size versus final concentration.

The experimental results of both short-term and long-term periods showed that under the same initial conditions, by increasing the diameter of the settlement column, the concentration of settled sediments first decreased and then increased.

This is because for a settlement column with a small diameter, the wall effect is significant, and there is a relatively small sediment weight, and the interaction between suspended sediments is weak. Therefore, the suspended sediments generally settle with a high average final velocity. Also, by increasing the settlement column diameter, the effect of the wall decreases, therefore it can be neglected by exceeding the column size from a certain limit. Simultaneously, under this condition, Brownian motion gives full play to the interaction and flocculation, thereby preventing the settlement and consolidation process of suspended sediments. Sediment settlement distinctions caused by settlement column size are internally induced by the equilibrium relationship among the effects of wall, convection, and flocculation. For a column cross-section of about 30 cm$^2$, the hindering effect of the settlement column will be maximized, leading to the minimum settlement and final consolidation.

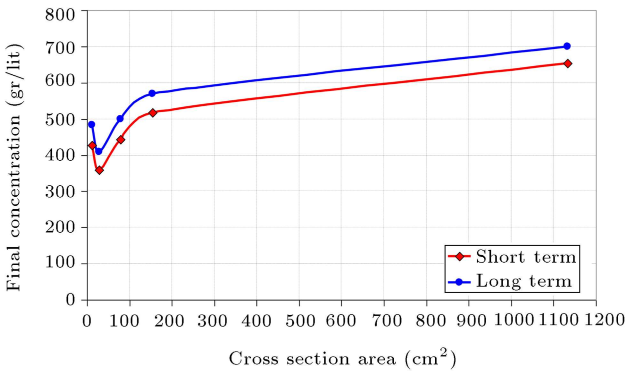


**Figure 10.** Settlement column size scenario.

### 3.4. Effect of temperature

The effect of temperature on the settling and consolidation cycles of cohesive sediments has been studied because of significant temperature variations in the water of dam reservoirs during the hot and cold seasons. In the summer and winter seasons, tests were conducted under the real temperature at the case study site. In this regard, both the cold temperature (less than 6°C) and the hot temperature (above 24°C) ranges and temporal variations in the relative sediment-water height ($H_f/H_0$) were measured for initial sediment concentrations of 50 and 100 g/l. Figures 11(a) and 11(b) illustrate the effects of temperature effect studies considering varying initial concentrations. The results have shown that the effect of temperature on the sedimentation process at low initial concentrations is less negligible, but its effect increases with excess concentration. Therefore, it can be shown that the effect of temperature on the settlement and consolidation process is less than other parameters such as initial height and initial concentration. The increase in the dry density of cohesive sediments with temperature could be due to the effect of temperature on the flocculation of cohesive sediments. In addition, water density is also dependent on the temperature and can affect the settlement and consolidation processes.

## 4. Conclusions

Settlement and consolidation of cohesive sediments are continuous development processes from liquid to plastic solid. In these processes, the effective stress is transferred to the sediment particles skeleton, and the excess pore water pressure is completely dissipated.

Finally, the following results were obtained from the performed experiments on settlement and consolidation of the cohesive sediments. Changes in the dry density in the initial stage were considered an essential part of the consolidation process. Higher pressure,

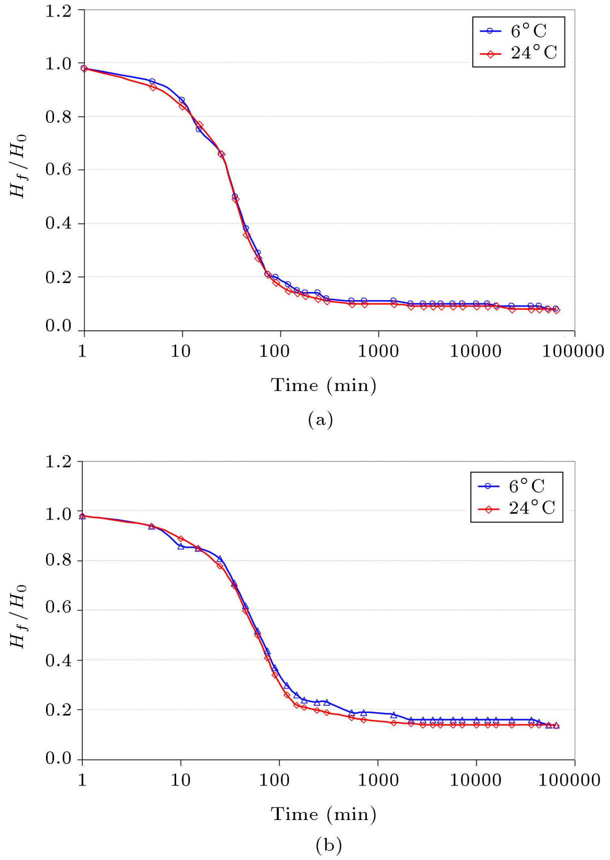


**Figure 11.** Temporal changes in $H_f/H_0$ for difference initial sediment concentration: (a) $C_0 = 50$ gr/lit and (b) $C_0 = 100$ gr/lit.

as well as the average distance between the sediment particles, accelerated the settlement of cohesive sediments. By increasing the concentration, the initial free settlement stage became longer. Experimental observations showed that due to the intensification of Brownian motion, the delayed settlement process occurred over a longer period by increasing the concentration. By increasing the initial concentration, there was a delay in the onset of the consolidation stage. Accordingly, in the first and sixth scenarios with initial concentrations of 25 g/l and 150 g/l, the samples started to consolidate under their weight after 1.5 h and 17.5 h, respectively. Observations showed that for a constant settlement column diameter, by a 50% decrease in the initial height of the water-sediment mixture, the settlement and consolidation processes in the second stage occurred 8 hours earlier. Observations showed that as the diameter of the settlement column and the initial height of the water-sediment mixture decreased by 60%, the settlement and consolidation process in the second stage is advanced by 9 hours. The experimental results showed that a threefold increase in temperature from 6°C to 24°C in all scenarios had an insignificant effect on the settlement and consolidation processes of cohesive sediments. This can be attributed to the negligible effect of water temperature on the Brownian motion. Experiments to investigate the effect of the cross-section of the settling column on the sedimentation process have also shown that walls can affect the long-term and short-term effects of the sedimentation process.

## Acknowledgement

The authors highly appreciate Jundi-Shapur University of Technology, Dezful, Iran for their supports.

## Nomenclature

| | |
|---|---|
| LL | Liquid Limit |
| PL | Plastic Limit |
| $G_s$ | Specific gravity of the sediment |
| SAR | Sodium Adsorption Ratio |
| K | Potassium |
| Na | Sodium |
| Mg | Magnesium |
| Ca | Calcium |
| $SO_4$ | Sulfur |
| Cl | Chlorine |
| $HCO_3$ | Bicarbonate |
| pH | pH of water |
| EC | Electrical Conductivity |
| $C_0$ | Initial concentration |
| $D$ | Diameter of column |
| $H_1$ | Initial sediment-water interface height |
| $H_f$ | Final sediment-water interface height |
| $T_t$ | Time |
| $T$ | Temperature |

## References

1. Tan, G. and Chen, Y. "Experimental study of cohesive sediment consolidation and its effect on seepage from dam foundations", *International Journal of Sediment Research*, **31**(1), pp. 53–60 (2016).
2. Tan, G.M., Jiang, L., Shu, C.W., Ping, L.V., and Jun, W.A. "Experimental study of scour rate in consolidated cohesive sediment", *Journal of Hydrodynamics*, **22**(1), pp. 51–57 (2010).
3. Fathi-Moghadam, M., Emamgholizadeh, S., Bina, M., and Ghomeshi, M. "Physical modelling of pressure flushing for desilting of non-cohesive sediment", *Journal of Hydraulic Research*, **48**(4), pp. 509–514 (2010).
4. Mueller, E.R., Grams, P.E., Schmidt, J.C., Hazel, J.E., Alexander, J.S., and Kaplinski, M. "The influence of controlled floods on fine sediment storage in debris fan-affected canyons of the Colorado River basin", *Geomorphology*, **226**, pp. 65–75 (2014).

5. Shadorvan, M., Lashkar-Ara, B., and Seyed Kaboli, H. "Assessment of the cohesive sediments fall velocity in Karkheh Dam reservoir", *Irrigation Science Engineering*, **41**(2), pp. 211–224 (2018).
6. Lashkar-Ara, B. and Fatahi, M. "On the measurement of transverse shear stress in a rectangular open channel using an optimal Preston tube", *Scientia Iranica*, **27**(1), pp. 57–67 (2020).
7. Lashkar-Ara, B., Kalantari, N., Khozani, Z.S., and Mosavi, A. "Assessing machine learning versus a mathematical model to estimate the transverse shear stress distribution in a rectangular channel", *Mathematics*, **9**(6), 596 (2021).
8. Wu, W., Perera, C., Smith, J., and Sanchez, A. "Critical shear stress for erosion of sand and mud mixtures", *Journal of Hydraulic Research*, **56**(1), pp. 96–110 (2017).
9. Mathew, R. and Winterwerp, J.C. "Surficial sediment erodibility from time-series measurements of suspended sediment concentrations: development and validation", *Ocean Dynamic*, **67**(6), pp. 691–712 (2017).
10. Schoellhamer, D.H., Manning, A.J., and Work, P.A. "Erosion characteristics and horizontal variability for small erosion depths in the Sacramento-San Joaquin River Delta, California, USA", *Ocean Dynamic*, **67**(6), pp. 799–811 (2017).
11. Khastar-Boroujeni, M., Esmaili, K., Samadi-Boroujeni, H., and Ziaei, A. "Wastewater effect on the deposition of cohesive sediment", *Journal of Environmental Engineering*, **144**(1), p. 04017083 (2018).
12. Krishnappan, B.G. "Cohesive sediment transport studies using a rotating circular flume", *7th International Conference Hydroscience and Engineering*, pp. 1–15 (2006).
13. Glasbergen, K., Stone, M., Krishnappan, B., Dixon, J., and Silins, U. "The effect of coarse gravel on cohesive sediment entrapment in an annular flume", *IAHS-AISH Proceedings and Reports*, **367**, pp. 157–162 (2014).
14. Haralampides, K., McCorquodale, J.A., and Krishnappan, B.G. "Deposition properties of fine sediment", *Journal of Hydraulic Engineering*, **129**(3), pp. 230–234 (2003).
15. Tran, D. and Strom, K. "Floc sizes and resuspension rates from fresh deposits: Influences of suspended sediment concentration, turbulence, and deposition time", *Estuarine, Coastal and Shelf Science*, **229**, p. 106397 (2019).
16. Guo, C., He, Q., Guo, L., and Winterwerp, J.C. "A study of in-situ sediment flocculation in the turbidity maxima of the Yangtze Estuary", *Estuarine, Coastal and Shelf Science*, **191**, pp. 1–9 (2017).
17. Guo, C., He, Q., van Prooijen, B.C., Guo, L., Manning, A.J., and Bass, S. "Investigation of flocculation dynamics under changing hydrodynamic forcing on an intertidal mudflat", *Marine Geology*, **395**, pp. 120–132 (2018).
18. Li, F.G., Xiong, X.Z., and Zhao, M. "Basic characteristics of muddy water with high concentration", *Yellow River*, **2**(4), pp. 31–32 (2006).
19. Tang, J., Wang, Y.P., Zhu, Q., Jia, J., Xiong, J., Cheng, P., Wu, H., Chen, D., and Wu, H. "Winter storms induced high suspended sediment concentration along the north offshore seabed of the Changjiang estuary", *Estuarine, Coastal and Shelf Science*, **228**, p. 106351 (2019).
20. Taheri, Z., Esmaili, K., Samadi, H., and Khodashenas, S.R. "Experimental investigation of the effect of consolidation time on erosion rate of cohesive sediment", *Irrigation Science Engineering*, **43**(2), pp. 171–186 (2020).
21. Guo, S.J., Zhang, F.H., Song, X.G., and Wang, B.T. "Deposited sediment settlement and consolidation mechanisms", *Water Science and Engineering*, **8**(4), pp. 335–344 (2015).
22. Xu, C., Chen, Y., Pan, Y., and Yu, L. "The effects of flocculation on the entrainment of fluid mud layer", *Estuarine, Coastal and Shelf Science*, **240**, p. 106784 (2020).

## Biographies

**Masoud Goudarzi** is a graduate student from the College of Civil Engineering at the Jundi Shapur University of Technology, Iran. He is interested in geotechnical and managing reservoir sedimentation.

**Babak Lashkar-Ara** is an Associate Professor in the College of Civil Engineering at the Jundi Shapur University of Technology, Iran. He received his PhD degree in Hydraulic Structures from Shahid Chamran University of Ahwaz, Iran. His research interests include river engineering, hydraulic of sediment transport, and physical hydraulic modeling. He has published many papers in reputable journals and international conference proceedings.

**Hesam Seyed Kaboli** is a Staff Member at the College of Civil Engineering, Jundi Shapur University of Technology, Iran. He received his PhD degree in Hydrology from Shahid Chamran University of Ahwaz, Iran. His research interests include the application of remote sensing and GIS for risk management.