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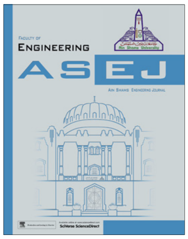

CIVIL ENGINEERING

Enhanced hydrosuction performance for cohesive sediment removal in low-head reservoirs

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Abstract Deposited sediment removal or dredging is generally required in many hydro-system projects. Siphon dredging or hydrosuction bears many advantages including low energy consumption, minor turbidity generation and ability of localized dredging. A new device attached to a regular siphon inlet is introduced which produces a swinging action by means of a simple mechanism. Equipped siphon sweeps a larger area than what a regular siphon does and enhances the hydrosuction performance for cohesive sediment removal. Regular and equipped siphon performances for dredging non-cohesive and cohesive sediments were investigated experimentally. Time to reach equilibrium scour was determined and applied for all the tests. The equipped siphon generated larger scour holes in cohesive sediment type than that of the regular one and enhanced sediment removal process. This could be attributed to the swinging action of the siphon inlet which strikes the scour hole wall and acts against the cohesion property of the sediment.

1. Introduction

Reservoir sedimentation has been recognized as the main factor drastically influencing dam's life span. The phenomenon becomes more important in arid and semi-arid regions, where the occurrences of flash floods are more frequent during which large amounts of sediment are transported. According to the International Commission On Large Dams, ICOLD, around 0.3 percent of large dam reservoirs capacity decreases annually due to reservoir sedimentation [1]. Some methods were implemented by engineers to act against reservoir sedimentation, including turbidity current ventilation, free flushing and pressurized flushing, mechanical excavation of dry materials, and siphon dredging [2].

Solid deposit could be removed by means of a siphon action, which is termed hydrosuction when it applies to reservoirs sediment removal. In this method, the flow field velocity in the vicinity of the siphon inlet generates sufficient shear stress to establish reservoir bed scour. The mixture of the water-scoured materials is then removed through the siphon to the downstream side of the reservoir.

Compared to other dredging methods, hydrosuction might remove a smaller volume of sediment in a specific period of

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time, but it exhibits some advantages such as local dredging capability, low turbidity generation, ease of use, flexibility in sediment release management and cost-effectiveness. Fine sediment attracts most organic and inorganic contaminants and bears high tendency for suspension during dredging process. Suspended sediment is difficult to collect and could easily travel to downstream reaches, which ultimately spread the pollution along the water course. Low turbidity generation during a dredging process and the capability of local sediment removal are the main advantages of hydrosuction, which make its application in such circumstances appropriate [3,4].

The first hydrosuction application was reported form Algeria where a 0.61 m diameter pipe of 1600 m length was used to dredge 1.4E6 m^3 of silt and clay during a 2-year period with an average mass concentration of 3% [5]. Also, about a century ago siphon dredging had been applied to remove deposited sediments from the intake mouth of the 21-m-high Rioumajou dam, in France. The siphon carried 15 kg of sediment in 1 cm s water [6]. It seems that China is the most experienced country in hydrosuction dredging. In this country, the sediment laden flow of the hydrosuction dredging systems has been supplied to agricultural croplands to fertilize the soil. The hydrosuction systems in China were employed in dams having heights between 15 and 35 m. Also, the successful application of hydrosuction in 1.8 m height Atkinson weir on Elkhorn River, which lacks desilting structure, was reported. The employed hydrosuction system removed as much as the annual sediment inflow [5].

Slotta [7] applied the dimensional analysis and proposed some relationships to represent the scour hole geometry for different types of experimentally tested materials. Gladigau [8] studied the influence of the suction inlet shape on the material removal. He reported insignificant impact of straight and bell-mouth type tube inlets on the geometry of scour hole. Salzmann [9] examined the hydraulic behavior of the flow around suction inlets in the vicinity of sand beds. He presented the velocity and pressure distribution around suction inlets in graphical forms and claimed that the potential flow theory could be applied for studying the flow condition around the suction inlet.

Rehbinder [10] followed the potential flow theory and considered the suction inlet as a sink point. He resolved the acting forces on sediment grains in two components, i.e. forces generated by seepage flow phenomenon and shear forces produced in the boundary layer in the immediate vicinity of the bed. Rehbider [10] indicated viscous flow present in a cylindrical region surrounding the pipe inlet where $0 < r < Z_o \frac{\sqrt{2}}{4}$, in which Z_o is the distance between the suction inlet mouth and the undisturbed bed surface. He also observed that the location of initiation of motion takes place at $0.8 < \frac{r}{z_o} < 1.4$ and the maximum force acts at $r \approx 0.8z_o$. Rehbinder revealed that the lift force acting on grains is a function of the vertical pressure distribution in the sediment layer and reported that the ratio of lift force to shear force changes between 2 to 20.

Ullah [4] provided relationships to describe the scour hole geometry at the equilibrium condition. He concluded that the scour hole profiles are similar in shape and could be represented by a common relationship. He also found that absence of a vortex beneath the suction inlet leads to formation of a conical heap at the center of the scour hole, while the presence of the vortex generates asymmetric scour hole shape and random values of sediment removal.

Recently, Chen et al. [11] proposed an inclined cutting shape for the siphon inlet along with peripheral holes slightly above the inlet to overcome chocking problems. They also connected the siphon inlet to a floating tank in order to generate vertical movements and reported the best performance of the system in connection with the inlet diameter to enhance chocking prevention.

The main objective of this research was to enhance the performance of the hydrosuction dredging by installing a specific turbine like device which locally disturbs the bed. This feature empowers the hydrosuction action and provides it with the ability of dredging cohesive sediment. The influence of installing the device on sediment removal efficiency for dredging cohesive and non-cohesive sediment is examined and reported.

2. Experimental setup and procedures

In this research a new device is developed which functions based on turbine principle and improves siphon dredging performance for cohesive sediment. The device should be installed at the siphon inlet to generate swinging or wobble motion with the aid of a special mechanism introduced herein. The mentioned action of suction inlet leads to sweeping a wider area compared to that of stationary siphon and prevents choking of the siphon.

As indicated in Figs. 1 and 2 the device consists of a cylindrical casing with an inlet and an exit. The exit is connected to the siphon mouth. Inside the cylindrical chamber an impeller is installed that rotates by the flowing water similar to the rotation of a turbine runner. The impeller shaft extends outside the casing on which a disk is connected. The disk rotates at the same speed of the impeller. The wobble motion of the device is generated by means of the rotation of an asymmetric weight installed on the disk. The disk and the connected weight are covered by a cap which was removed for presentation purpose in Fig. 1. Fig. 2 presents the details of the device parts.

During the first stage of the design, different impeller configurations, as indicated in Fig. 3, were manufactured and tested. The preliminary test indicated that impeller of type C performed better than the other two types did.

To examine the device performance a series of experiments were carried out on a regular siphon and a siphon equipped

Figure 1 The proposed device.

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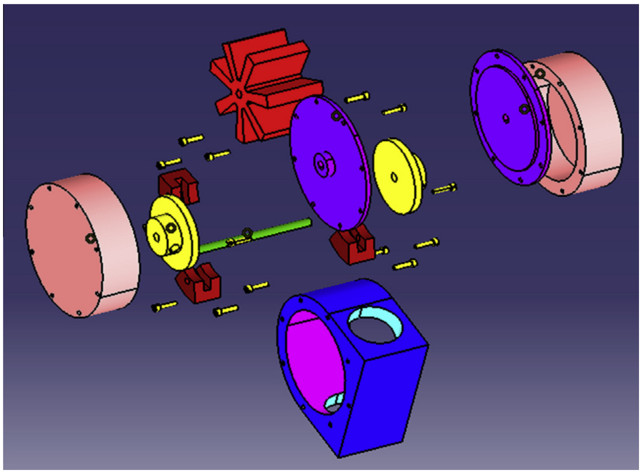

Figure 2 Details of the device parts.

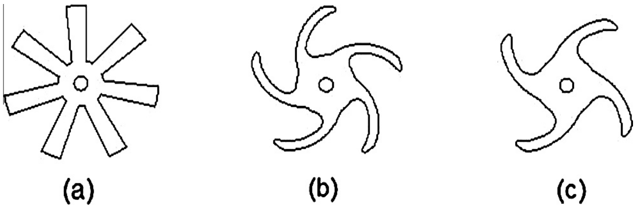

Figure 3 Tested impeller configurations.

with the device. The experiments were performed in the Central Hydraulic Laboratory of the Irrigation and Reclamation Engineering Department, University of Tehran. A 100 cm long, 50 cm wide and 60 cm deep tank was used as a reservoir which was installed on a platform 250 cm high above the ground level (Fig. 4). A tank was used to collect the water released from the siphon outlet. Also a centrifugal pump circulated the water between the tanks. The water which enters the main tank went through a turbulence reduction system. A 15 cm sediment layer was placed on the reservoir bed. A 2.5 cm diameter corrugated flexible plastic pipe was used as siphon pipe while attached to a point gauge to set the distance to the bed during the test of the regular siphon. The siphon exit discharges the water–sediment mixture into a sediment trap box from which the clear water was released into the water collection tank.

Four uniform sediment types were examined. Two cohesive types were used which have median grain sizes of 0.015 mm and 0.005 mm and were referred to as SI and CL, respectively. Plasticity index for SI is about 9 and for CL is about 17; therefore, it is inferred that CL is more cohesive than SI. Also, two non-cohesive sediment types were tested which have median

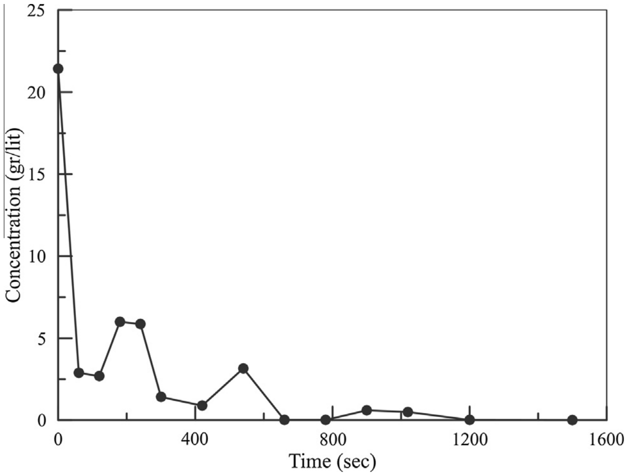

Figure 5 Time variation of sediment concentration.

Table 1 Head loss coefficient of ordinary and armed siphon.

Siphon state	Head loss coefficient
Ordinary siphon	4.79
Chamber	1.55
Impeller	3.03
Wobble disk	0.78
Device	5.35
Equipped siphon	10.14

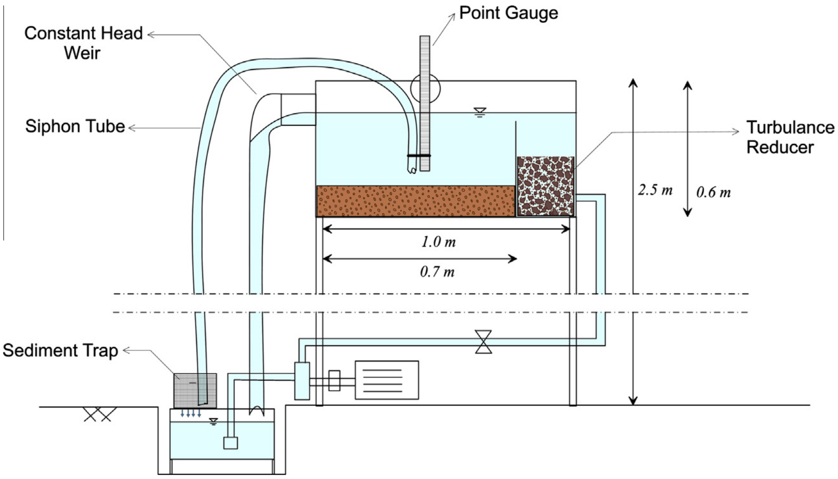

Figure 4 A schematic of experimental apparatus.

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grain sizes of diameter of 0.25 mm and 0.63 mm and were referred to as FS and CS, respectively.

The equipped and the regular siphons were evaluated based on their scouring and sediment removal performances. The time to equilibrium state is a fundamental factor in scouring research. Accordingly, initial experiments to determine the time to equilibrium state were performed using regular siphon with siphon inlet close to the bed (Z_o = 0) and the FS sediment type. The results are presented in Fig. 5 which indicates that steep decrease in the sediment concentration took place within the first few minutes and it became negligible after the 10th minute. It seems that during the initial stage of the scouring process, the scour hole reaches its maximum depth and produces rather steep wall side. Afterward the wall slope flattens by the movements of the material from the wall side to the deepest part of the hole. The material then is removed by the suction process. However, the time to equilibrium for the main experiments was 20 min. The total head between the reservoir and the water collecting tanks was 2.4 m and kept constant for all experiments. Also, the siphon discharge was measured by means of volumetric method.

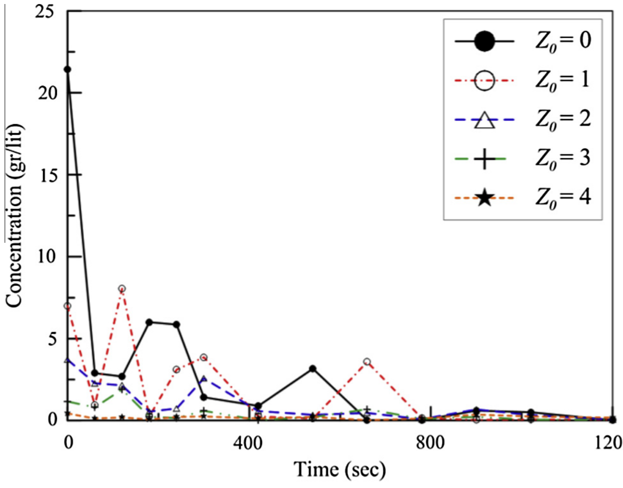

Figure 6 Time-concentration variation for above bed setting of suction inlet.

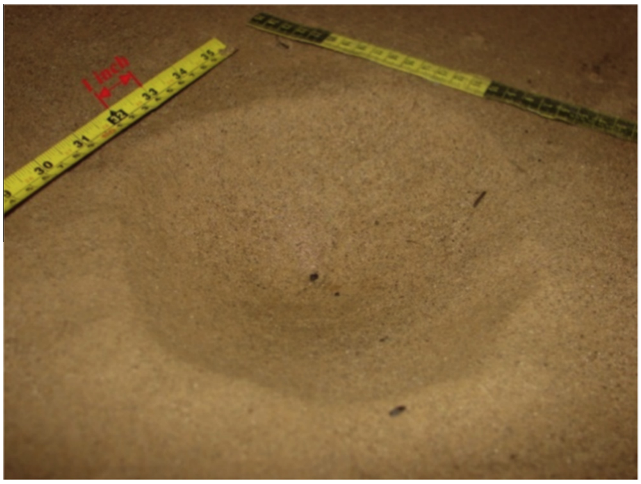

Figure 7 Scour hole, ordinary siphon, FS sediment, Z_0 = 2.5 cm.

3. Results and discussion

Preliminary tests to determine the head loss coefficients, *k* (ratio of total available head, 2.4 m, to the velocity head of outflow from siphon tube), of the siphon were arranged. Relatively short siphon length was used in these tests; therefore, the coefficient represents the cumulative losses of friction along the siphon tube and the minor losses of siphon inlet, exit, and bends. The results are reported in Table 1. Knowing the head loss of the regular siphon, the device was installed at the siphon inlet and the procedure was repeated to determine the loss coefficients for each part of the device (Table 1). The Data in Table 1 indicate that among other parts of the device, the

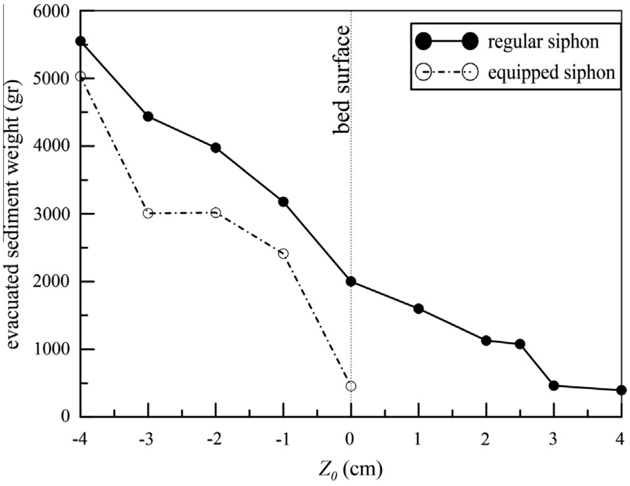

Figure 8 Comparison of sediment removal capability of regular and equipped siphon against inlet distance to the bed level for FS sediment type.

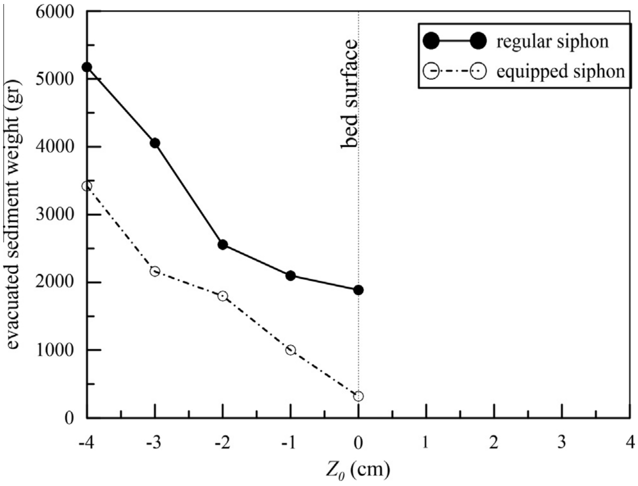

Figure 9 Comparison of sediment removal capability of regular and equipped siphon against inlet distance to the bed level for CS sediment type. (a) SI cohesive sediment type and (b) CL cohesive sediment type.

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impeller presented the highest head loss which highlights the importance of the impeller design.

3.1. Non-cohesive sediments

In the first set of experiments the impact of the siphon inlet distance to the undisturbed sediment bed on the sediment removal process was examined. These experiments were performed using the FS sediment type and the regular siphon with $Z_o = -4, -3, -2, -1, 0, 1, 2, 2.5, 3,$ and 4 cm. The data of time evolution of sediment removal were collected for $Z_o = 0$–4 cm, but the total sediment weight for all tested distances was recorded. The results of the time evolution data are presented in Fig. 6.

The variation of the time evolution of the sediment concentration, which could be considered as a function of the scour hole depth, reveals the random nature of the phenomenon. The variation of the outflow mixture concentration is indeed a consequence of the materials sliding action of the scour hole wall. As the time evolution of the scour hole depth reaches its equilibrium state, the variation of the sediment removal process decreases drastically. Fig. 6 shows that decreasing the siphon inlet elevation drastically intensifies the sediment removal within the initial period of the process. Accordingly, the second set of the experiments were conducted with subsurface siphon inlet installation. Fig. 7 shows a sample scour hole for $Z_o = 2.5$ cm and FS sediment type. The absence of a conical heap at the hole center and the wall asymmetry indicates the presence of vortices beneath the siphon inlet as reported by Ullah [4].

In the next step, the siphon was equipped with the device and the total sediment removal for $Z_o = 0, -1, -2, -3, -4$ installation depth was recorded. The results were recorded along with the results of regular siphon data in Fig. 8. Due to higher head loss value of the equipped siphon in comparison with the regular siphon, the former generally releases about 30% less water sediment mixture than the latter does. However, a glance at Fig. 8 reveals that by deepening the siphon inlet in the sediment bed, the sediment removal capability of the equipped siphon slightly tends to that of regular siphon. This might mostly be attributed to the angle of repose of the sand rather than the device action, mainly because such a tendency was not observed with the results of CS sediment tests as indicated in Fig. 9.

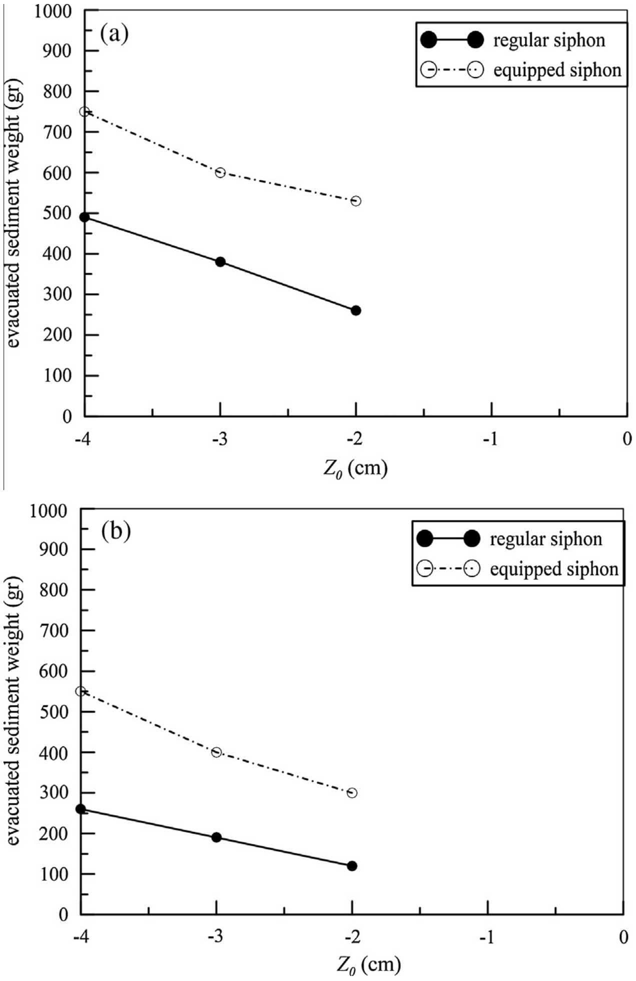

Figure 10 Comparison of sediment removal capability of regular and equipped siphon against inlet distance to the bed level for (a) SI- and (b) CL cohesive sediment types. (a) Ordinary siphon and (b) equipped siphon.

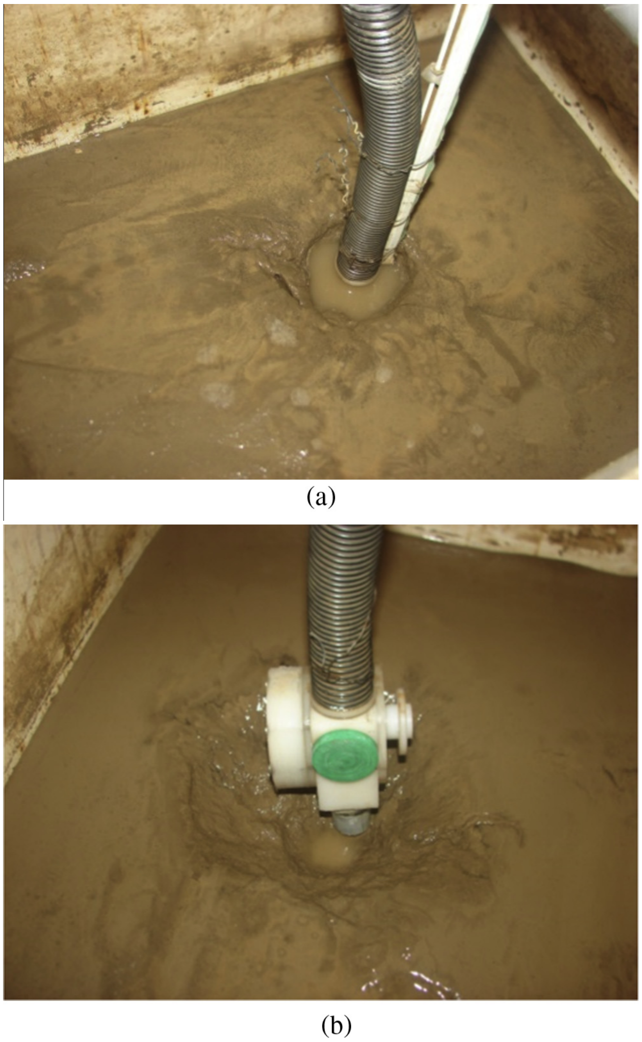

Figure 11 Scour hole at SI sediment, $Z_0 = -4$ cm.

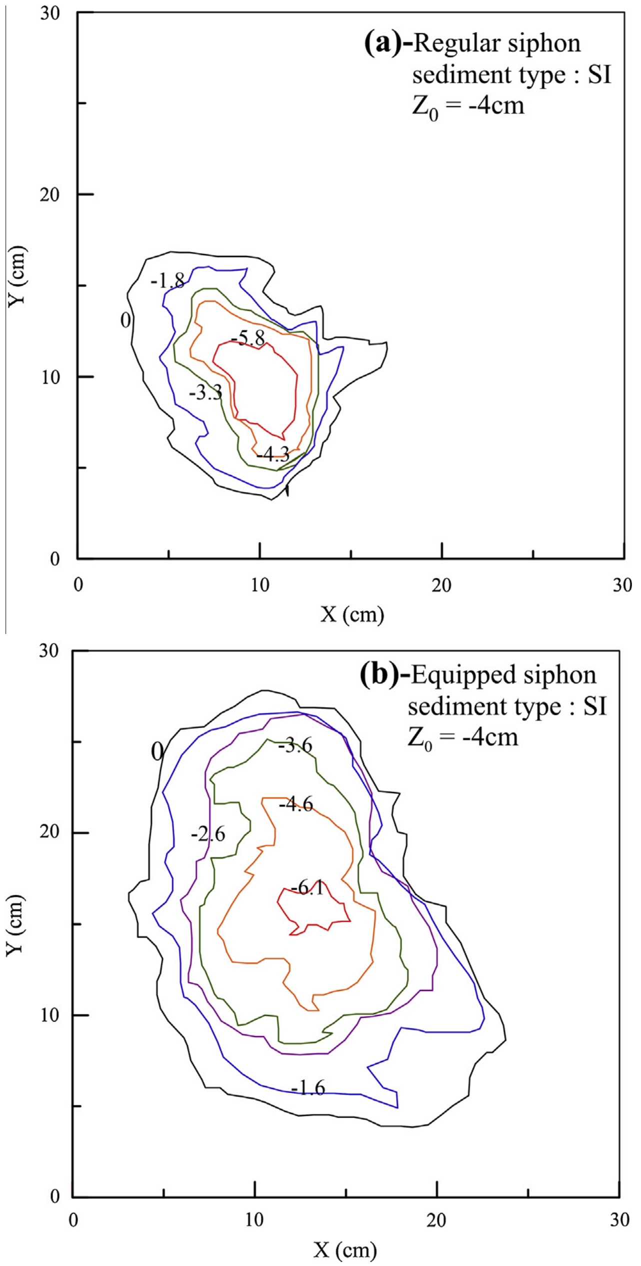

Figure 12 Topography contour of scour holes generated in SI sediment type: (a) regular siphon and (b) equipped siphon.

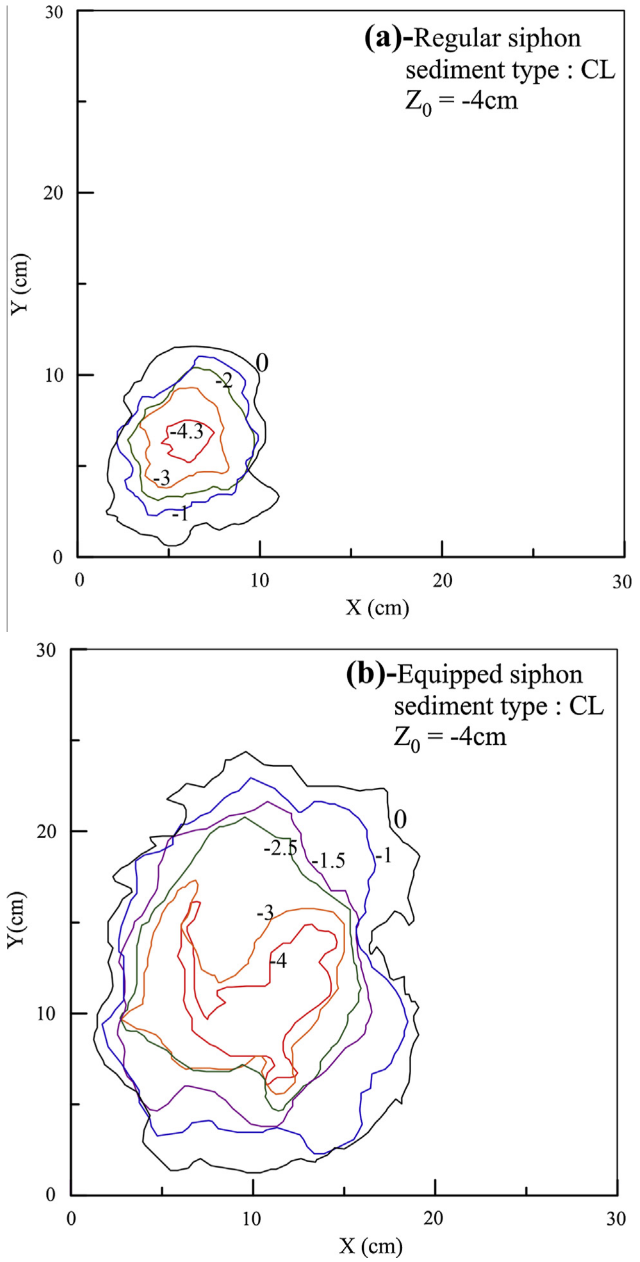

Figure 13 Topography contour of scour holes generated in CL sediment type by (a) regular siphon and (b) equipped siphon.

3.2. Cohesive sediments

Preliminary tests using regular siphon and the SI-type cohesive sediment indicated that sediment removal capability decreases drastically as the inlet distance from the bed level increases. Accordingly, the tests of the cohesive sediments were carried out for $Z_o = -2, -3$ and -4 cm. The data of the removed sediments by both siphon types are presented in Fig. 10 for both SI and CL sediment types. The figure clearly indicates the advantage of the equipped siphon over the regular one for cohesive sediment removal. It is evident that the higher the cohesive property of the sediment, the better the performance of the equipped siphon is (Figs. 10a and b).

Obviously, the cohesive property of examined sediment types prevents the failure of the scour hole wall. Consequently, the regular siphon generates a cylindrical scour hole having a diameter slightly larger than the siphon diameter (Fig. 11a). The wobble motion forced the equipped siphon inlet to strike the scour hole wall and remove the scoured material through the siphon action. Accordingly, the equipped siphon generates a conical shape scour hole which is much larger than that of regular siphon (Fig. 11b). Also, Figs. 12 and 13 present the contour of the depth variation of the scour hole for both types of the cohesive sediments generated by the regular and the equipped siphon, respectively. The figures reveal the influence of the device movements on enlarging the scour hole and the amount of the sediment removal. This highlights the advantage of the device application for cohesive sediment removal. However, further studies are required to minimize the head loss of the device components in order to improve its performance.

4. Conclusions

A new device was designed to improve the performance of hydrosuction process for cohesive sediment. The device, which generates a swinging movement, should be installed at the siphon inlet. The performance of sediment removal of the regular siphon and siphon equipped with the proposed device was experimentally tested for two types of non-cohesive and two types of cohesive sediments. All the experiments were run to reach the equilibrium state the period of which was determined during the initial experimental program. In non-cohesive sediments the results indicated that the regular siphon performed better than the equipped one does. This could be attributed to the instability of loose material of the scour hole wall and the lower head loss value of the regular siphon compared to the equipped one.

In the case of cohesive sediment, the cohesive property prevents scour hole wall failure when the regular siphon was used. That is, an almost typical cylindrical shape of scour hole with diameter slightly larger than that of the siphon tube, was generated. While the collision of the inlet of the equipped siphon with the scour hole wall acted against the cohesion property, eroded wall materials and enlarged the scour hole drastically compared to that of the regular siphon. Such advantage was achieved even though the head loss of the equipped siphon was much higher than that of the regular one. This implies that the equipped siphon removed larger amount of sediment with smaller amount of water which itself could be considered as an advantage in some circumstances. Also, the results indicated that increase in the cohesion property of sediment intensifies the performance and enhances the efficiency of the equipped siphon compared to that of the regular one. Optimizing the head loss of the device components would increase the equipped siphon performance drastically, which requires further studies.

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