Al-Azhar University Civil Engineering Research Magazine (CERM
Vol. (43) No. (2) April . 2021

Pilot Study Based on Employing New Bed Material ToReduce Scour downstream Hydraulic Structures

Ibrahim M.M.[*1], Helmy A.[*2],Alafrawi M.A.[*3], El-Hazek A.N.[*1]

[1]Faculty of Engineering at Shoubra, Cairo, Benha University, Egypt
[2]Faculty of Engineering, Al-Azhar University, Cairo, Egypt
[3]Pyramids Higher Institute for Engineering and Technology, 6th October City, Egypt

الملخص العربى :

النحر هي ظاهرة طبيعية تحدث خلال سريان المياه خلال المنشآت المائية المقامة بطول نهر النيل بهدف التحكم في تصرفات و مناسيب المياه خلال فصول السنة المختلفة. نتيجة لما تسببه ظاهرة النحر من مشكلات تهدد إستقرار هذه المنشآت المائية من حدوث أضرار تخص العناصر الإنشائية المكونة لهذه المنشآت. تم عمل دراسات مختلفة بهدف إيجاد حلول هندسية تختص بتقليل النحر الناشئ خلف البوابات مثل إستخدام مواد معاد تدويرها للعمل كقاع للمجرى المائي بهدف عمل مقاومة للنحر الناشئ نتيجة سريان المياه وإستخدام قاعدة خرسانية مدعمة برقائق من الصاج المعرج. في هذه الدراسة تم عمل 72 تجربة مع إجراء تغيير علي العديد من المتغيرات مثل إستخدام قيم مختلفة من التصرفات وإستخدام نسب خلط مختلفة بين الرمل والسليكا بهدف الوصول إلى أنسب نسبة خلط بينهما مع إجراء التجارب المعملية بإستخدام طريقتي خلط مختلفين إما بإضافة الماء أو بخلط الرمل والسليكا خلط جاف. أثبتت النتائج أنه بزيادة نسبة خلط السليكا مع الرمل في حالة خلطهم خلط جاف يزداد النحر الحادث مع العكس تقل نسبة النحر بزيادة نسبة السليكا في حالة خلطهم خلط في وجود المياه وأيضا تزداد نسبة النحر بزيادة التصرفات و بتقليل عمق المياه أسفل النموذج المعملي نتيجة إنخفاض السرعة.

Abstract:

Scour is very critical, a natural phenomenon that affects the stability of the hydraulic structure in Egypt such as barrages, spillways due to its erosive effects on the structural elements such as piers, gates, and bed material of the water channel. Several studies focused on using different methods to minimize scour effect such as end sills, corrugated apron, and employing recycled material and used it as bed material. In this experimental study, using silica fume with fine sand as a bed material seemed to be very effective in reducing scour downstream sluice gate. A laboratory flume inthe Faculty of Engineering, Al-Azhar University, Egypt was used as a simulation of water flow through a hydraulic structure with a gate. Several parameters were studied such as the effect of scour in case of changing the value of discharge (22, 24, and 29 L/sec), tailwater's depth (18, 20, and 22 cm), the percentages of silica fume added to fine sand (0, 1, 5, and 10%) in addition to the type of mixture (with water and without water).72 experimental runs were performed and the scour was measured after each attempt. The results showed that increasing the percentage of silica fume has an effective role in minimizing the scour in the case of adding water to the mixture of sand and silica fume. Also, increasing the discharge and decreasing the tailwater's depth increased the scour that occurred downstream the sluice gate.

Keywords: scour, hydraulic jump, silica fume, discharge, hydraulic structures.

1. Introduction

Egypt is one of the countries that has several hydraulic structures due to the presence of the Nile river to control the amount of water flow through the main, branch, and distribution canals. Despite the proper design of these hydraulic structures such as bridges, spillways, regulators, locks, and weirs, all the previous hydraulic structures face a lot of problems during water's flow causing fetal problems which affect the stability of these structures which represents a critical issue to the other fields such as irrigation and navigation that depends mainly on these hydraulic structures[1].

Water flows through the Nile river with a specific velocity and this velocity increases with excessive value while passing through any hydraulic structure constructed along the Nile river due to the small sectional area of these hydraulic structures compared to the sectional area of the Nile river. This excessive flow velocity caused a natural phenomenon related to the water's flow called scour [2]. Scour downstream any hydraulic structure can cause massive damage to the foundations, piers, and bed materials causing a structural failure to these structures [3]. Scour can cause erosive damage as it can produce shear stress, if the shear stress is higher than the bed material shear stress, scour will take place [4].

To avoid these destructive effects produced from scour, a proper understanding of the scour must be done. Scour is not a sudden phenomenon but it takes many stages from forming to desperation. The first stage of the scour is called the "initial stage" where all the erosive effects and damages take place due to the very high rate of velocity. Then, scour was transferred to the next stage called the "development stage" where the rate of scouring became slower than the initial stage. Finally, scour moved to a final stage called the "equilibrium stage" where there is no change to scour's depth and any changesthat take place to the scour's depth became non-observed [5].

As a result of these critical effects of scour downstream the hydraulic structures, several engineering solutions are used to minimize the scour effect by dispersing the energy produced from the high flow's velocity. An example of these engineering solutions is using sills downstream of any hydraulic structures.The used sills are with different shapes and dimensions in addition to the usage of different materials to allow a safe flow with a minimum scour [6]. Another popular technique used is using different materials of the solid apron to disperse the energy from the produced scour as many studies used a corrugated apron with a specific apron's length [7]. Another technology was using air injection to create air bubbles to minimize the flow velocity as a way to reduce scour's effect [8].

The direction of the research these days was using alternative materials instead of non-cohesive bed materials to strengthen the resistance of the bed of the canal to reduce the shear strength produced from scour. Among all the used materials, Gabion Mattresses is one of the most effective materials used due to the remarkable effect on reducing the scour to safe levels[9].

The present research aims to study the effect of using alternative material instead of the popular bed material such as fine sand to reduce the scour produced downstream gates, barrages in addition to any hydraulic structure. Also, studying the effect of parameters' variations on the scour to reach the proper control considerations.

2. Dimensional analysis

This section is investigated to create a mathematical relationship between the different parameters that control the water flow and the produced scour. So, this analysis can be performed depending on the algebraic method used called the "Buckingham method". The following equation represents the factors affecting the scour downstream of the sluice gate:

$$f\left(l_f\ , B, b, b_o, w_{sand}, w_{silica}\ , Q, V, H_u, y_b, y_t, \rho, \mu, g, \rho_s, D_{50}, \Phi, D_s, L_s, L_m\right) = 0 \quad (1)$$

Some of the previous parameters a constant in our experimental studies such as the length of the solid apron (L_f), themedian si: of the used bed material (D_{50}), and the angle of internal friction between sand particles (Φ). So, the previous equation can be modified into the following equation:

$$f\left(B, b, b_o, w_{sand}, w_{silica}\ , Q, V, H_u, y_t, D_{50}\ , y_b, \rho, \mu, g, D_s, L, L_m\right) = 0 \quad (2)$$

By applying the Buckingham method to the previous equation, it will be in the new form:

$$f\left(\frac{B}{y_t}, \frac{b}{y_t}, w_{sand}, w_{silica}\ , \frac{D_{50}}{y_t}, \frac{y_1}{y_t}, \frac{y_b}{y_t}, \frac{H_{up}}{y_t}, \frac{Q}{V.yt^2}, \frac{\mu}{V.\rho.y_t}, \frac{y_t.g}{V^2}, \frac{D_S}{y_t}, \frac{L}{y_t}, \frac{L_m}{y_t}\right)=0 \quad (3)$$

Due to the turbulent flow that occurred in this experimental study, Reynolds number is ranged from 3000 up to 30000, so, it can be neglected. And the final form will be as the following:

$$\frac{D_S}{y_t} = f\left(\frac{L}{y_t}, \frac{D_{50}}{y_t}, \frac{Q}{V.yt^2}, F_r, \frac{w_{sand}}{w_{silica}}, \frac{H_{up}}{y_t}\right) \quad (4)$$

3. Materials and Methods

3.1. Laboratory Flume's description

The experimental work was performed inthe hydraulic laboratory flume of the Civil Engineering Department, Faculty of Engineering, Al-Azhar University, Egypt as shown in Figure (1). All the descriptions of this flume including apparatus, dimensions, and usage were illustrated in Table (1).

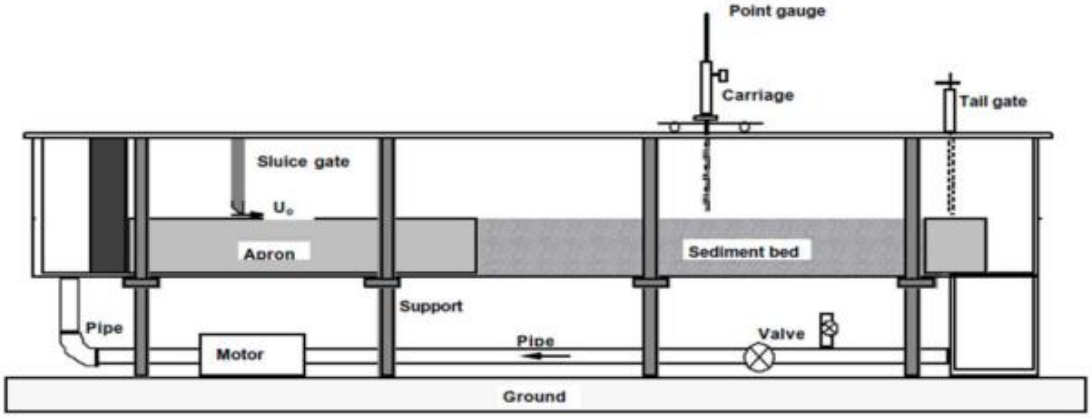

Figure 1. The used laboratory flume

Table 1. Full description of the laboratory flume.

Unit	Parameters	Values
Ground reservoir	Shape	Square
	Material	Bricks
	Length×Width×Depth	1.5 m×1.5 m× 0.5 m
Head tank	Shape	Rectangular
	Material	Steel
Tail tank	Shape	Rectangular
	Material	Steel
Main flume	Flume section	Rectangular
	Length×Width×Depth	4 m×0.3m× 0.5 m
	Type of sidewall material	polycarbonate
	Floor	Based on steel truss
Gate	Material	Steel
	Length×Width×Depth	0.4 m×0.3 m×0.001 m
Weir	Type	calibrated sharp-crested weir
	Shape	Rectangular
	Dimensions	Width of 0.25 m
	Material	Copper
Lifting Pump	Capacity	150 L/Sec
	Delivering head	10 m

At the beginning of the water flow, water may flow in a turbulent mode. So, to avoid that turbulence, a gravel box was used at the upstream water flow, to convert the flow from turbulent water flow to laminar water flow to avoid any effect on the results of the scour values.
Some apparatus was used for measuring the water and bed levels to estimate the amount of scour that occurred after each experimental trial. The X-y carriage was fixed in the laboratory flume, this x-y carriage can move along the laboratory flume for measuring the water and bed levels at any desired levels. In addition to the x-y carriage, scour point gauge was employed to estimate the water and sand levels in addition to establishing a contour map along the laboratory flume.
In this experimental study, additives were added to the fine sand (non-cohesive bed material). Silica fume was used as a Nano-material to minimize the scour downstream sluice gate. The characteristics of fine sand and silica fume used in this experimental study are illustrated in Table (2). Also, grain size distribution of fine sand is shown in Figure (2).

Table (2). Characteristics of fine sand and silica fume.

Material	**Parameters**	**values**
Fine sand	Density	1500 kg/m^3
	The median size of fine sand	0.6 mm
	Layer thickness	8 cm
Silica fume	Bulk density	310 kg/m^3
	Specific surface area	15 m^2/g
	Particles shape	Cylindrical

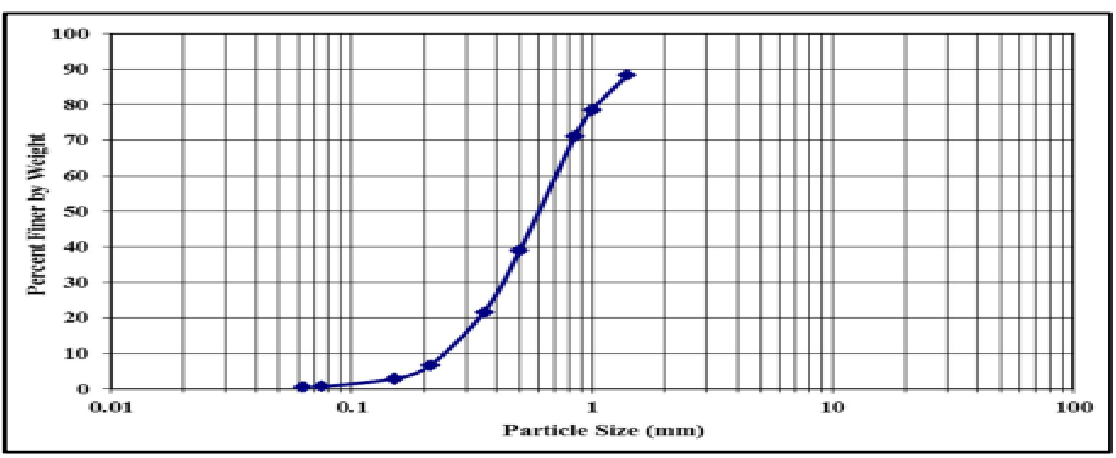

Figure 2. grain size distribution of the used fine sand

3.2. Steps of experimental study

In this experimental study, studying the effect of mixing silicafume with fine sand was performed with different parameters such as the flow discharge, tailwater depth, percentage of mixing silica fume with fine sand, and the type of mixture. 72 experimental runs were performed and divided into two groups (A and B) depending on the variables of the experimental study as shown in Table (3).

Table 3. The various parameters used in this experimental study.

Groups	Discharge, L/sec	Tailwater's depth, cm	(% mixture)	Type of Mixture
Group A	22, 24, 29	18, 20, 22	0, 1, 5, 10	Dry (without water)
Group B	22, 24, 29	18, 20, 22	0, 1, 5, 10	Wet

1. First, the laboratory flume was prepared for the experimental study by establishing a bed material from fine sand with a depth of 8 cm as shown in Table (2).
2. At the beginning of the experiment, no flow was found as there is no water pumped through the channel, where this was performed by keeping the sluicegate closed.
3. To start water flow, water was pumped through the flume when the lifting pump was turned on.
4. As the flow discharge is a variable parameter, the discharge was controlled through the lifting pump by operating it on different discharge values (22, 24, and 29 L/sec).
5. To operate the experiment with different tailwater depths (18, 20, and 22 cm), the main controller was the tailgate, which can control the tailwater depth by changing its opening height.
6. The mixture between fine sand and silica fume was performed in a rectangular dry wooden box with zero moisture content (WC=0) to avoid any change in the mixture percentage that affects the scour results. To ensure the proper mixing between fine sand and silica fume, the mixture process was continuous until the color of the hybrid material became homogenous.
7. The amounts of silica fume added to fine sand was expressed as (0, 1, 5, and 10%), the amount of used sand was 36 kg to fill a length of 100 cm, a width of 30cm in addition to a depth of 8 cm. So, the weight of silica fume used was as illustrated in Table 4.

Table 4. weight of silica fume corresponding to % silica fume

Materials	Mixture percentage	Weight
Silica fume	1%	36 gram
Silica fume	5%	180 gram
Silica fume	10%	360 gram

8. Depending on the results obtained from previous researchers, each experimental attempt was performed for a run duration of 300 minutes.
9. After operating all the 72 experimental attempts, the water flow was stopped by turning off the lifting pump.
10. To estimate the bed levels and to determine the occurred scour, all the water was drained by fully opening the tailgate, so, the water took its direction to the tail tank

3.3. Description of experiment

To simulate the effect of the scour on the bed material during each trial of the 72 experimental runs, a wide mesh was established. This mesh consists of more than 120 points distributed in 6 lines with an interval of 0.05 m to be able to give the proper description of the bed of the flume after each experimental run.

4. Results and discussions

4.1. Scour characteristics due to the % silica fume

Figure (3.a) illustrates the effect of mixing silica fume with fine sand with four different silica fume percentages (0, 1, 5, and 10%) in the case of mixing both materials without adding water to the mixture.

It was clear that the scour depth at each case of the mixture was -2.1 cm, 2.3 cm, 3.1 cm, and 4.42 cm for using silica fume with a mixing percentage of 0%, 1%, 5%, and 10%, respectively. From figure (3.a), it was observed that increasing the silica fume percentages was able to increase the scour depth by 109%, 147%, and 210% at 1% silica, 5% silica, and 10% silica, respectively.

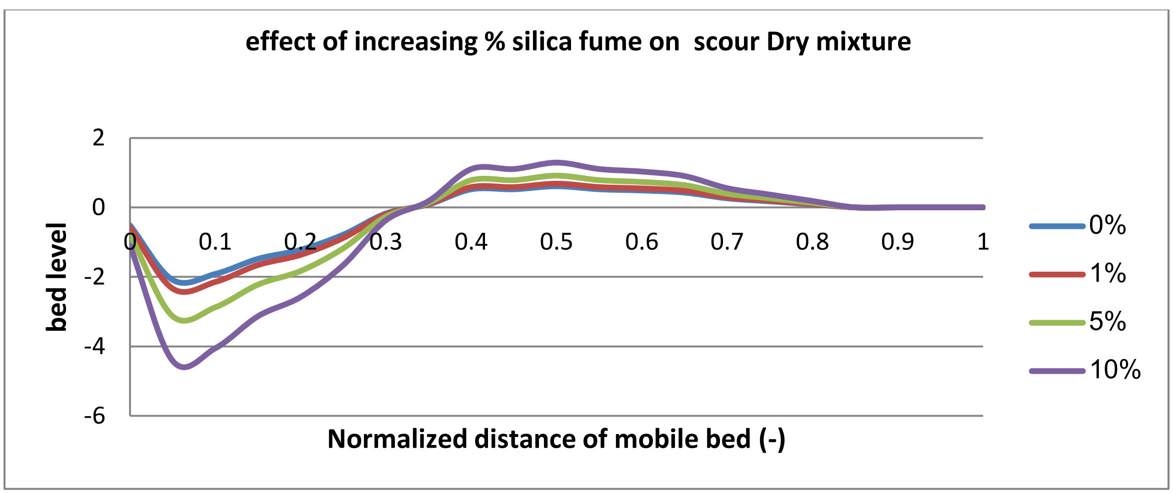

Figure (3.a). The centerline bed profile for 0%, 1%, 5%, and 10% Silica fume

(y_t=18 cm& Q=22 L/sec & dry mixture)

The increase of the scour value was due to the type of mixture between fine sand and silica fume. In this case, silica fume and sand were mixed without adding any amount of water (dry mixture) in addition to the characteristics of silica fume that enhanced the separation between silica fume particles and sand particles [10]as shown in Table 5.

Table 5. silica fume characteristics

Parameters	Values
Shape of particles	Very fine – spherical shaped
Specific gravity	2.2 -2.3
Mean size	0.1 – 0.3 μ.m

From Table (5), it was clear that silica fume has a weight lower than sand that allowed the silica fume particles to move during water flow causing an increase in scour's value. Also, the particle shape was spherical which prevented any bond between it and sand particles[11], [12].

Figure (3.b) shows the effect of using different percentage of silica fume (0, 1, 5, and 10%) on the scour occurred downstream the sluice gate in case of mixing fine sand and silica fume with adding water to form a wet mixture.

The maximum scoursthat occurred downstream sluice gate were 2.1 cm, 1.9 cm, 1.4 cm, and 0.97 cm while using 0% silica fume, 1% silica fume, 5% silica fume, 10% silica fume, respectively. So, it was clear that increasing silica fume percentages in the case of the wet mixture between sand and silica has a remarkable effect on decreasing the scour downstream sluice gate.

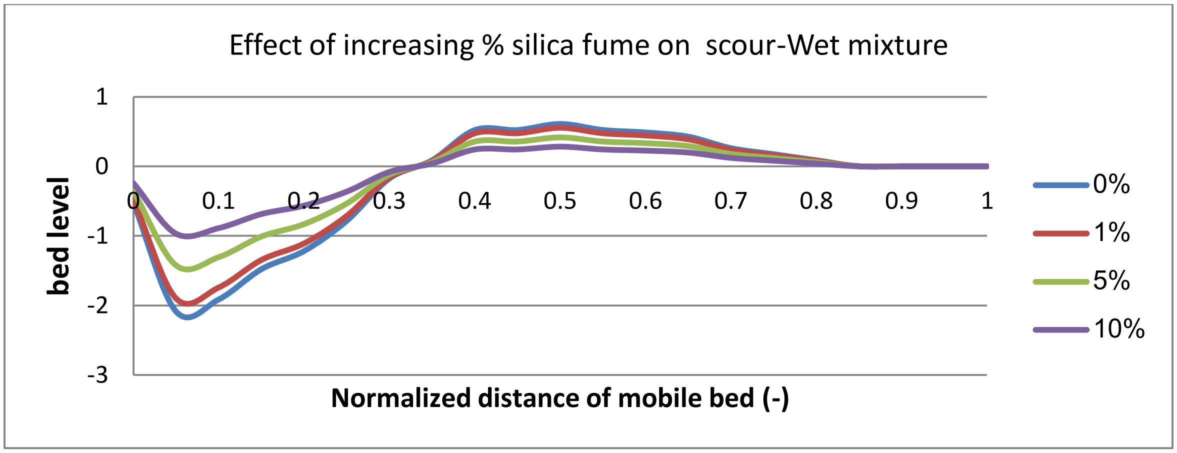

Figure (3.b). The centerline bed profile for 0%, 1%, 5%, and 10% Silica fume (y_t=18 cm& Q=22 L/sec &wet mixture)

From Figure (3.b), increasing % silica was able to minimize the scour depth by 10%, 33.3%, 53.8% at 1% silica fume, 5% silica fume, 10% silica fume, respectively. The performance of the mixture between silica fume and fine sand was due to the full interaction between sand and silica fume, so the combination was performed as one unit. This new mixture was successful in dispersing a large amount of energy of water flow that was the main reason for decreasing the scour downstream sluice gate.

4.2. Scour characteristics for the studied model

Figure (4.a) illustrates the effect of increasing the discharge on the scour downstream the sluice gate. It was observed that the maximum scour value at different discharge values (22, 24, and 29L/sec, at constant gate opening of 1.5 cm, the tailwater depth was 18 cm, and the mixture between fine sand and silica fume was dry)was 2.1 cm, 2.6 cm,3.15 cm at 0% silica fume and increased to 4.4 cm, 5.3 cm, and 5.7 cm at 10% silica fume.

So, increasing the discharge value from 22 L/sec to 29 L/sec while the gate opening was constant (1.5 cm), the flow's velocity increased by increasing the discharge value. This high velocity had a big effect on moving the sand and silica fume particles from their location during water flow especially in the case of mixing silica fume with fine sand in a dry mixture and without adding any amount of water that enhanced the separation between sand and silica fume by increasing the discharge.

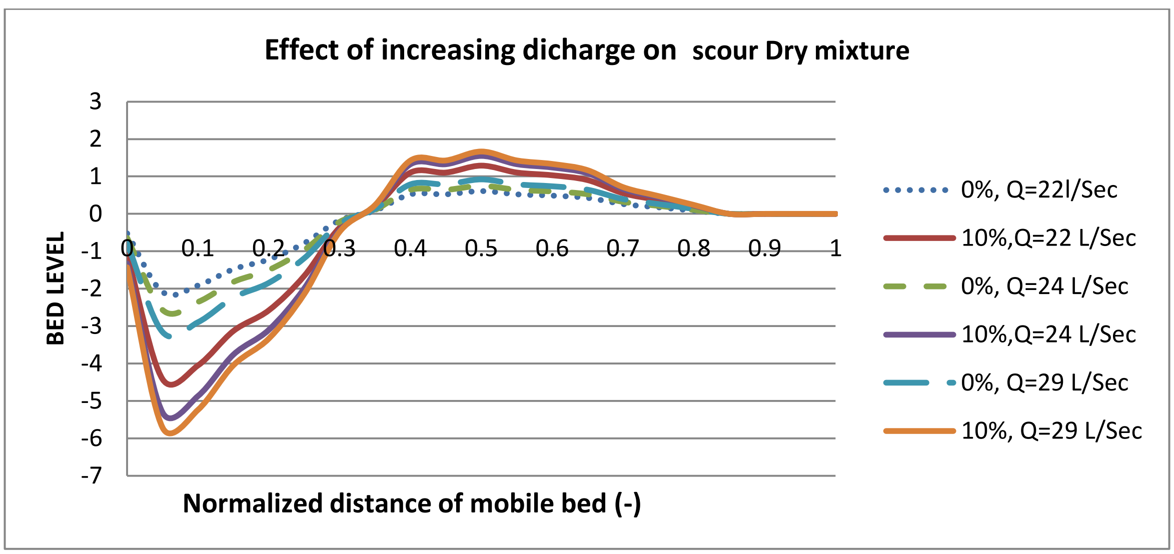

Figure (4.a). The centerline bed profile for 0%, and 10% Silica fume at different discharge values (y_t=18 cm&bo=1.5 cm L/sec &Dry mixture)

In a contract of the case of dry mixture between silica fume and fine sand, from Figure (4.b), the remarkable effect of mixing silica fume with sand with adding water forming a wet mixturewas clear. This type of mixture has a role in minimizing the scour downstream the sluice gate despite increasing the discharge value (Q= 22 L/sec, Q= 24 L/sec,Q= 29 L/sec).

From Figure (4.b), the maximum scour occurred downstream the sluice gate was 2.1 cm, 2.6 cm, 3.15 cm at tailwater's depth of 18 cm while the flow discharge was 22 L/sec, then the maximum scour value decreased at 10% silica fume at the same value of discharge (22 L/sec) to 1.03 cm, 1.27 cm, and 1.6 cm. So, the performance of the mixture between silica fume and sand was very effective in minimizing the scour due to the high interaction between the particles of both materials, where this high bond developed a sufficient resistance to water's flow that prevented scour downstream sluice gate.

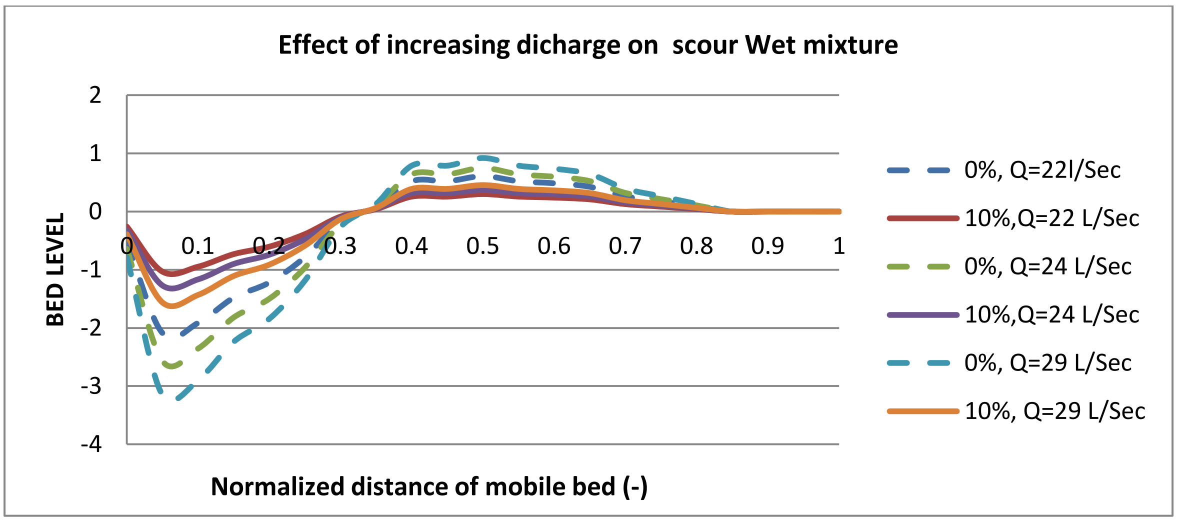

Figure (4.b). The centerline bed profile for 0%, and 10% Silica fume at different discharge values (y_t=18 cm& bo=1.5 cm L/sec &Wet mixture)

4.3. Scour characteristics due to the depth of Tailwater (y_t)

To study the effect of increasing the tailwater's depth on the scour downstream the sluice gate, several experimental trials were performed by increasing the tailwater's depth from (18 cm to 20 cm, and 29 cm), while a constant discharge value of 22 L/sec in case of mixing sand and silica fume in a dry mixture without adding water in addition to the case of adding water to form a wet mixture.

For the dry mixture shown in Figure (5.a), the maximum scour was 2.1 cm, 1.6 cm, and 0.2 cm while using 0% silica fume at tailwater's depth of 18 cm, 20 cm, and 29 cm; while the maximum scours at 10% silica fume were 4.4 cm, 3.3 cm, and 2.2 cm at yt of 18cm, 20cm, and 29 cm, respectively. So, increasing the tailwater's depth made a remarkable decrease in scour values downstream the sluice gate. That was because the tailwater's depth causes a decrease in the flow's discharge that was the reason behind decreasing the scour downstream sluice gate.

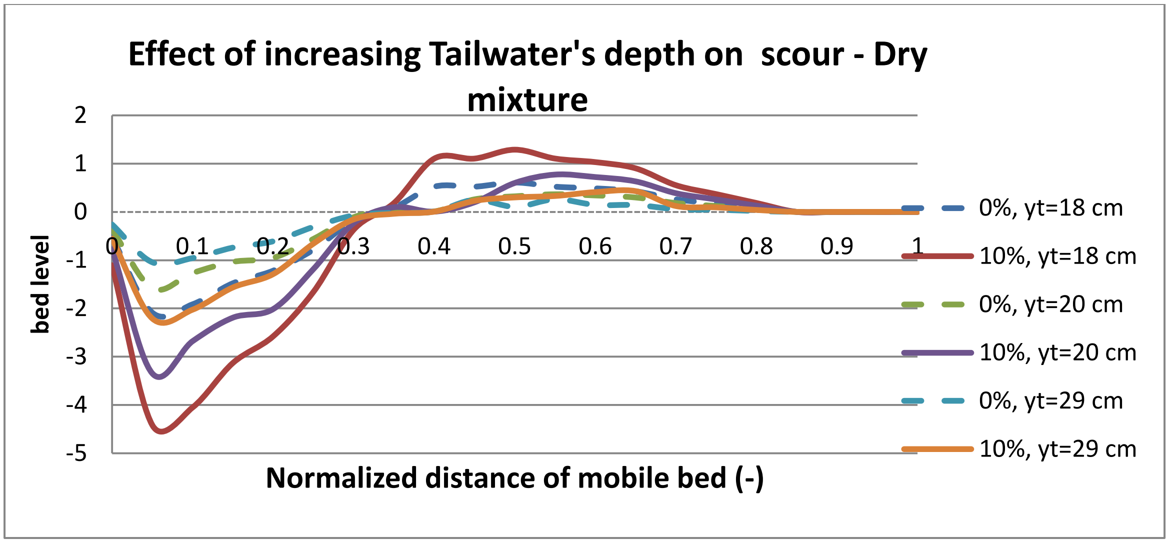

Figure (5.a). The centerline bed profile for 0%, and 10% Silica fume at different Tailwater depth (bo=1.5 cm&Q= 22 L/sec &Dry mixture)

For the wet mixture shown in Figure (5.b), the maximum scour was 2.1 cm, 1.6 cm, and 1.1 cm while using 0% silica fume at tailwater's depth of 18 cm, 20 cm, and 29 cm; while the maximum scours at 10% silica fume were 1.1 cm, 0.8 cm, and 0.5 cm at yt of 18 cm, 20 cm, and 29 cm, respectively. So, increasing the tailwater's depth made alsoa remarkable decrease in scour values downstream the sluice gate. That was because the tailwater's depth causes a decrease in the flow's discharge that was the reason behind decreasing the scour downstream sluice gate.

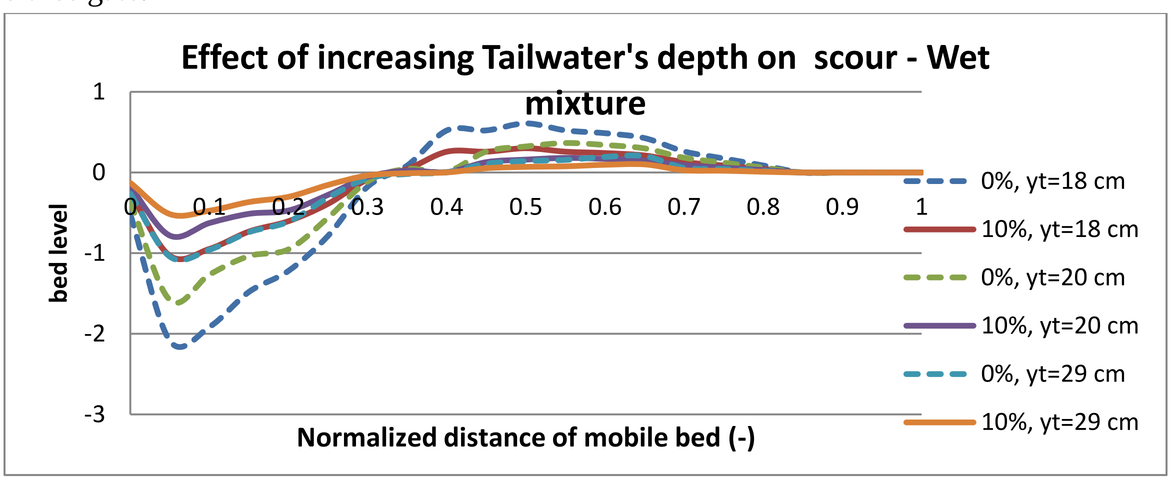

Figure (5.b). The centerline bed profile for 0%, and 10% Silica fume at different Tailwater depth (bo=1.5 cm &Q= 22 L/sec &Wet mixture)

5. Conclusion

Egypt faces critical issues associated with the scour that occurred downstream several hydraulic structures such as barrages, regulators, and spillways that affect the stability of hydraulic structures as it causes remarkable damage to piers, abutments, and gates. An experimental study was performed based on several variables such as the percentage of silica fume, the type of mixture between fine sand and silica fume (Wet and Dry mixtures), the discharge, and the tailwater's depth. The results of this experimental study concluded that increasing % silica was able to minimize the scour depth by 10%, 33.3%, 53.8% at 1% silica fume, 5% silica fume, and 10% silica fume, respectively in case of the wet mixture between silica fume and fine sand. Also, increasing the silica fume percentages was able to increase the scour depth by 109%, 147%, and 210% at 1% silica, 5% silica, and 10% silica, respectively in case of dry mixture between sand and silica fume. Also, increasing the discharge and decreasing the tailwater's depth increased the scour that occurred downstream the sluice gate.

Definition of symbols

Symbol	Definition
LF	Length of rigid apron behind the gates
B	Flume width
b	Gates width
b_o	Gate opening height
n	Number of opened gates
b	Total width of opened gates
e	Expansion ratio
Q	Discharge passing through the gates
V	Flow velocity
Fr1	Froude number
H_{up}	Upstream water depth
y_t	Tailwater depth
y_1	Depth of the water jet
y_2	Backwater depth
g	Gravitational acceleration
ρ	Density of water
µ	Dynamic viscosity of water
ρ_s	The density of bed material
D_{50}	The median size of bed material
Φ	The angle of internal friction
Ds	Maximum scour depth
L s	Length of scour hole formed downstream the rigid apron
Lm	Distance between the end of the floor and the maximum scour depth
W_{sand}	weight of fine sand
W_{silica}	Weight of silica fume

References

[1] A. Bonev and A. Alexandrov, “No TitleБагачина – тракийски култов център (предварително съобщение),” *Археология*, vol. 1, no. August, pp. 117–125, 1993.

[2] A. Mazumdar, “Local scour around hydraulic structures,” no. January 2009, p. 1263, 2016, DOI: 10.1201/9781315644479-199.

[3] K. K. Mohammad, M. Mohd, and A. Javed, “Bridge Pier Scour: A review of mechanism, causes, and geotechnical aspects,” *Age Amu Aligarh*, no. April 2016, pp. 1–6, 2016, [Online]. Available: https://www.researchgate.net/publication/312499136_Bridge_Pier_Scour_A_review_of_mechanism_causes_and_geotechnical_aspects.

[4] S. O. Lee, “Physical modeling of local scour around complex bridge piers,” 2006, [Online]. Available: https://smartech.gatech.edu/handle/1853/29398.

[5] M. Koken and G. Constantinescu, “An investigation of the flow and scour mechanisms around isolated spur dikes in a shallow open channel: 2. Conditions corresponding to the final stages of the erosion and deposition process,” *Water Resources Research*, vol. 44, no. 8, pp. 1–16, 2008, DOI: 10.1029/2007WR006491.

[6] O. K. Saleh, A. M. Negm, and N. G. Ahmad, “Effect of asymmetric side sill on scour characteristics downstream of sudden expanding stilling basins,” *Al-Azahr Engineering 7th International Conference. Cairo Egypt*, no. January 2003.

[7] M. E. Basiouny, T. H. Nasrallah, and F. S. Abdelhaleem, “Use corrugated beds to improvement downstream local scour Characteristics,” vol. 9, no. 7, pp. 6–10, 2018.

[8] R. T. R. Tipireddy and B. D. Barkdoll, “Scour Reduction by Air Injection at a Cylindrical Bridge Pier: Experimental Determination of Optimal Configuration,” *Journal of Hydraulic Engineering*, 2019, DOI: 10.1061/(ASCE)hy.1943-7900.0001555.

[9] T. Craswell and S. Akib, “Reducing Bridge Pier Scour Using Gabion Mattresses Filled with Recycled and Alternative Materials,” *Eng*, vol. 1, no. 2, pp. 188–210, 2020, DOI: 10.3390/eng1020013.

[10] S. Mindess, *Developments in the formulation and reinforcement of concrete*. Elsevier, 2019.

[11] “The new pozzolan (silica fume) has attracted the attention of many researchers. Research has been conducted in various parts of the world (e . g . Norway, Canada, United States, Japan) to study various aspects of using silica fume in concrete,” vol. 6, no. 3, pp. 357–375, 1995.

[12] “Physical properties and chemical properties of silica fume | Silica fume supplier in china,Microsilica manufacturer |.” https://microsilicachina.com/physical-chemical-properties-silica-fume/ (accessed May 05, 2021).