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Investigation of using sill under gate as a scour countermeasure downstream of a sluice gate

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A B S T R A C T

Scour is a natural phenomenon caused by the removal of soil from bed caused by a stream's erosion, which happens around or next to moving water structures. Various studies have been conducted to understand better local scour events in order to construct hydraulic structures safely and economically. This paper investigated the use of a sill under the gate and its effect on the maximum scour depth downstream of a sluice gate. The experiments were performed at different relative sill heights (h_s/L_s = without sill, 3.8, 8.0, 12.0, and 15.0%), and with various relative gate openings (a/Ls) of 13%, 18%, and 23%. The results revealed the effectiveness of the sill under the gate in decreasing the maximum scour depth. All sill heights reduced the maximum scour depth downstream of the sluice gate. The relative sill height of 8% gave the minimum value of the maximum relative scour depth for all relative gate openings. The results of this study can be used in the design considerations for gates and their protection.

1. Introduction

Scour is the process by which water removes soil particles from a channel's bed and banks. Scour can occur from both natural variations in the channel's flow and also human activity like constructing structures there or dredging material out of the bed. Failure of hydraulic structures is a worldwide concern that is mainly caused by local scouring. Hydraulic diverging jumps may be computed by a back-water curve, starting at an appropriate control section in upstream channel, and proceeding downstream along the expanding channel Hager [1]. Many studies were done to reduce the local scour downstream a sluice gate; such as Alireza [2], Ibrahim[3], Valinia et al., [4], El-Saeed et al., [5]. Many studies have controlled the hydraulic jump downstream of a sluice gate [6–8]. **Wafaie** [9] conducted an experimental study of the free rectangular hydraulic jump phenomenon on a rough channel bed with dentate, solid, zigzagged bed sills under various flow conditions using a variety of bed sill heights and bed sill placements. **Negm et al.** [10] conducted an experiment to investigate the effect of different ratios of rapidly expanding stilling basins on the scour characteristics downstream at the movable soil. **Ohtsu et al.** [11] investigated undular hydraulic jumps with a fully developed inflow systematically in horizontal rectangular channels. **Negm** [12] presented the effect of sill arrangement on maximum scour depth downstream of abruptly enlarged stilling basins. **Dey and Barbhuiya** [13] A 3-D turbulent flow field was built in a scour hole at a semi-circular abutment using a clear water regime. **Melville et al.** [14] determined the minimum dimensions for various

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flow depths, flow velocities, and apron application levels to protect a wing-wall abutment from scouring under mobile-bed conditions. **Yanmaz and Kose** [15] investigated time-dependent characteristics of scour holes around vertical wall abutments under clear water conditions with uniform bed materials. **Abou-Seida et al.** [16] Investigated the local scour around vertical bridge abutments in sand soils to predict the local scour pattern that will occur around the bridge abutment under equilibrium conditions. **Kose and Yanmaz** [17] indicated that a variety of problems may result from bridge failures over wide rivers. **Taymazet et al.** [18] used a 3D numerical model to carry out a numerical simulation of the maximum depth of scour caused by the construction of slots in various angles of flow attacks (SSIIM program). **Abdelhaleem** [19] suggested that local scour downstream hydraulic structures could suffer damage or complete breakdown, resulting in a loss of life and property. **Gupta et al.** [20] investigated and examined the impact of the approaching Reynolds number in addition to the approach Froude number. **Pagliara and Palermo** [21] To estimate the subsequent depth and the roller length in a variety of geometric and boundary configurations, a semi-theoretical approach was presented. **Ted et al.** [22] investigated the scour downstream of a stilling basin under different headwater and tailwater conditions. **Hamidifar H. et al**. [23] use a bed sill to study local scour downstream of a stiff apron. **Farhoudi and Shayan** [24] focused on using adverse stilling basins for reducing the local scour downstream the sluice gate, where a sub-merged wall jet issued from a sluice gate. They stated that as the length and slope of the stilling basin increased, the maximum depth of the scour hole decreased while its longitudinal dimensions increased. **Mohamed and Mahmoud** [26] used side flow jets to reduce scour techniques with the advantages of eliminating the jet clog produced from sediments and suspended solids. **Ibrahim M. et al.** [27] demonstrated that the type of mix (dry-mix or wet-mix) had a significant influence on the geometry of scouring and silting for the same flow conditions and the mixed percentage ratio of Silica fume. The current study aims to investigate the effect of using sills with varying relative heights under a sluice gate on scour downstream of the sluice gate.

2. Experimental work

The Hydraulics Laboratory, Faculty of Engineering, Benha University, conducted the experimental work. The used flume is shown in Figure 1 and has dimensions of 0.4 m in width, 0.6 m in height, and 15.0 m in length. The flume is provided with an instrument carriage. A flow metre was installed to measure the discharge that feeds the flume. The model scale is presented in Table 1.

The apron was followed by a 2.5 m long mobile bed consisting of a sand layer. The thickness of the sand layer is 20 cm. The sieve analysis of the sand layer is shown in Figure 2. The required time for each test, in which the relationship between ds/ds max. was plotted against the time as shown in Figure 3 , It was found that, equilibrium of maximum scour depth was achieved after 4 hours.

Fig. (1) General view of the flume.

Table 1. Definition of the experimental models.

Discharge (L/s)	*28*	*Stilling basin length (cm)*	*100*
Upstream water depth (cm)	25 to 50	Sill height (cm)	1.5 to 6
Tail water depth (cm)	15 to 30	Sill length(cm)	40
Gate opening (cm)	5,7 and 9	Sill width (cm)	10

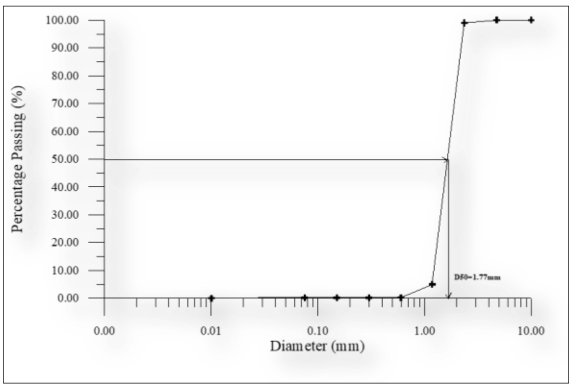

Fig. (2) Sieve analysis of the sand.

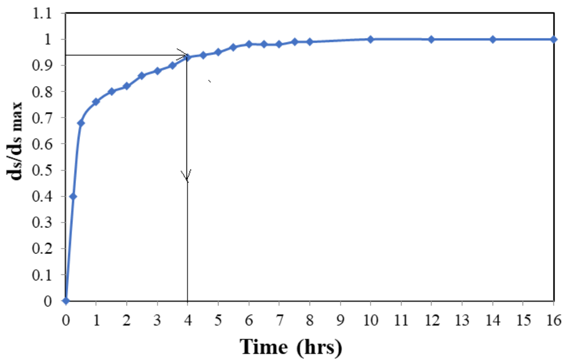

Fig. (3) Time scour relationship for Q = 28 L/S

3. Dimensional analysis

Dimensional analysis is used to define the dimensionless variables, as shown in Figure 4. Using the assessment of all the different comparisons, the scour downstream gate may be described as a function of the following variables:

$$d_s = f\,(\rho,\ \mu,\ a,\ h_s,\ y_t,\ v,\ L_s,\ g) \qquad (1)$$

Choosing (ρ, V, Ls) as repeating variables. The number of Π groups = 9-3 = 6 Π. These dimensionless parameters can be written in the following form:

$$\Pi 1 = \rho^{a1}\, v^{b1}\, Ls^{c1}\ \mu\ ,\ \Pi 2 = \rho^{a2}\, v^{b2}\, Ls^{c2}\ a\ \ ,\Pi 3 = \rho^{a3}\, v^{b3}\, Ls^{c3}\ \ hs,\ \ \Pi 4 = \rho^{a4}\, v^{b4} Ls^{c4}\ ds\ ,\ \Pi 5 = \rho^{a5}\, v^{b5} Ls^{c5}\ \ yt\ .\ \Pi 6 = \rho^{a6}\, v^{b6} Ls^{c6}\ g \qquad (2)$$

Then let $\Pi = M^0\, L^0\, T^0$ and solve for (ai, bi, ci):

$$\left(\pi_1 = \frac{\mu}{\rho v L_s}, \pi_2 = \frac{a}{L_s}, \pi_3 = \frac{h_s}{L_s}, \pi_4 = \frac{d_s}{L_s}, \pi_5 = \frac{y_t}{L_s}, \pi_6 = \frac{gL_s}{v^2}\right) \qquad (3)$$

After rearranging the above groupings, the following important relationship may be discovered:

$$\left(f = \frac{\mu}{\rho v L_s}, \frac{a}{L_s}, \frac{h_s}{L_s}, \frac{d_s}{L_s}, \frac{y_t}{L_s}, \frac{gL_s}{v^2}\right) \qquad (4)$$

The following independent variables can be used to express the maximum depth of scour downstream of the gate:

$$\frac{d_s}{y_t} = f\left(\frac{h_s}{L_s}, \frac{a}{L_s}, F_t, R_n\right) \qquad (5)$$

<u>Where:</u> a: gate opening (m), h_s: sill height (m), L_s: length of sill length (m), y_t: tail water depth (m), μ: viscosity of water (t/m/s), ρ: density of water (t/m^3), V: mean velocity (m/s), g: gravity acceleration (m/s^2), R_n: Reynolds Number and F_t: Tail Froude Number.

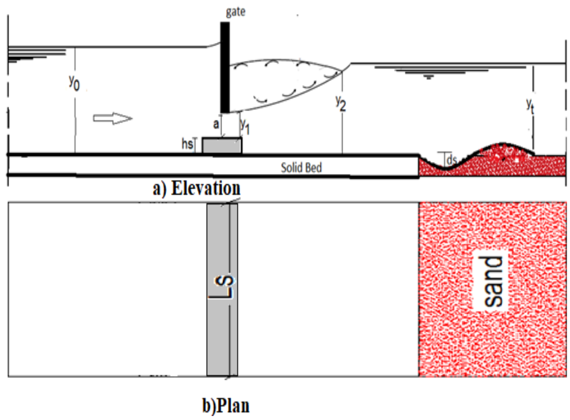

Fig. (4) Definition the experimental models

4. Analysis and discussion

The main objective of the experiment is to examine the effect of the sill height on the max scour depth downstream the sluice gate. Table 2 shows the results of the experiment for all relative gate opening and relative sill height.

Table 2: Experimental data of effect gate opening

Max scour depth	*Gate opening*	*without sill*	*hs/Ls = 3.80%*	*hs/Ls = 8%*	*hs/Ls = 12%*	*hs/Ls = 15%*
ds/yt	*a/Ls =13%*	*0.67*	*0.47*	*0.4*	*0.57*	*0.63*
	a/Ls =18%	*0.7*	*0.53*	*0.5*	*0.6*	*0.62*
	a/Ls =23%	*0.63*	*0.52*	*0.5*	*0.54*	*0.58*

4.1. Effect of relative height of sill (h_s/L_s) on the scour

4.1.1. Relative gate opening (a/L_s = 13%)

Figure (5) shows the relation between maximum relative scour depth (d_s/y_t) and tail Froude number (F_t) at various relative sill heights at a relative gate opening of (a/L_s = 13%). From the figure, it is observed that the scour depth increases with increasing tail Froude number (F_t) for all sill heights. The maximum scour depth values at the low values of tail Froude number (F_t) are close to each other's, but at the higher values of tail Froude number (F_t), the maximum scour depth values are separated from each other's. Figure 6 shows the relationship between the maximum relative scour depth (d_s/y_t) and the different relative sill heights at tail Froude number F_t = 0.4. According to Figures 5 and 6, the best relative height of the sill under the gate was (h_s/L_s= 8%) when compared to the gate without a sill.

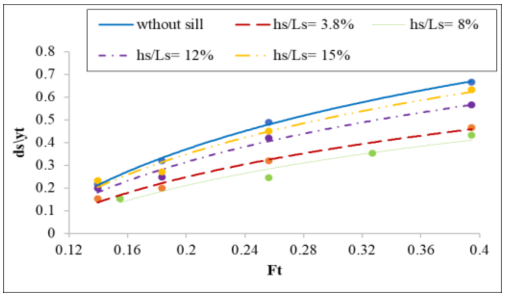

Fig. (5) The relation between maximum relative scour depth (d_s/y_t) and tail Froude number (F_t) for various relative sill heights at (a/L_s = 13%).

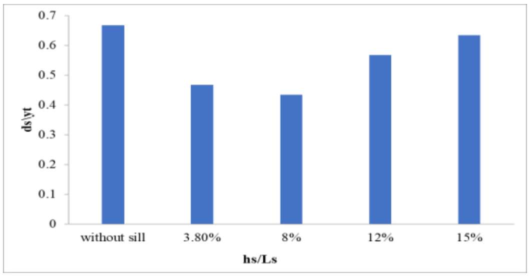

Fig. (6) The relation between maximum relative scour depth (d_s/y_t) and different relative sill height (h_s/L_s) at (F_t = 0.4) at a relative gate opening (a/L_s = 13%)

4.1.2. Relative gate opening (a/L_s = 18%)

Figure (7) shows the relation between maximum relative scour depth (d_s/y_t) and tail Froude number (F_t) for different relative sill heights at a relative gate opening of (a/L_s = 18%). From the figure, it is observed that the scour depth increases with increasing tail Froude number (F_t) for all sill heights. Figure 8 shows the relation between maximum relative scour depth (d_s/y_t) and different relative sill heights at a tail Froude number F_t = 0.4. From these figures, it is clear that the relative sill height of 8% gives the minimum value of the maximum relative scour depth.

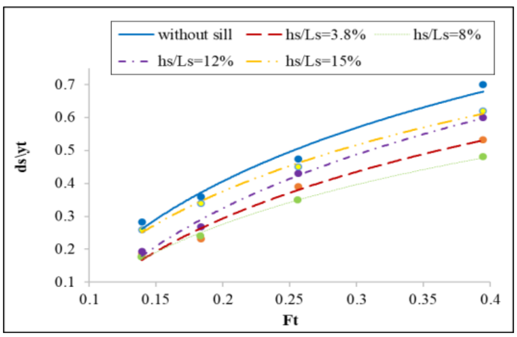

Fig. (7) the relation between maximum relative scour depth (d_s/y_t) and tail Froude number (Ft) for various relative sill heights at (a/L_s = 18%)

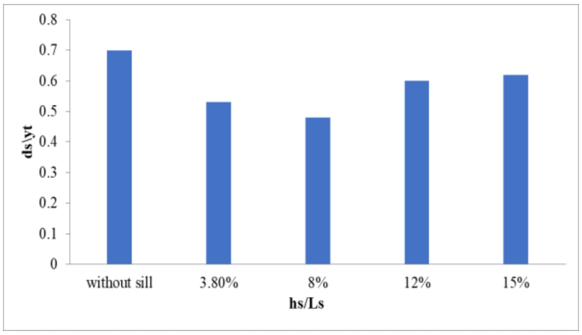

Fig. (8) The relation between maximum relative scour depth (d_s/y_t) and different relative sill height (h_s/L_s) at (F_t = 0.4) at a relative gate opening (a/Ls = 18%).

4.1.3. Relative gate opening (a/L_s = 23%)

Figure (9) shows the relation between maximum relative scour depth (d_s/y_t) and tail Froude number (F_t) for different relative sill heights at a relative gate opening of (a/L_s = 23%). Figure (10) shows the relation between maximum relative scour depth (d_s/y_t) and different relative sill heights at tail Froude number F_t = 0.4.

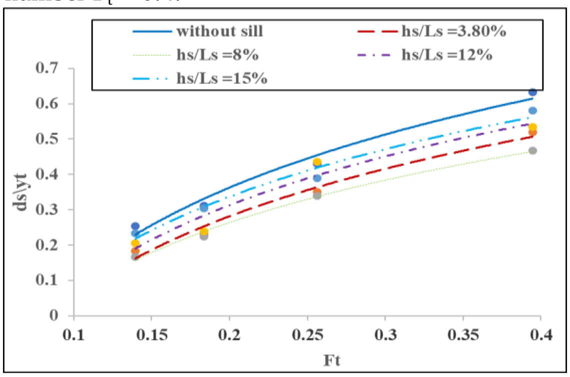

Fig. (9) The relation between maximum relative scour depth (ds/y_t) and Tail Froude number (F_t) for various relative sill heights at (a/L_s = 23%).

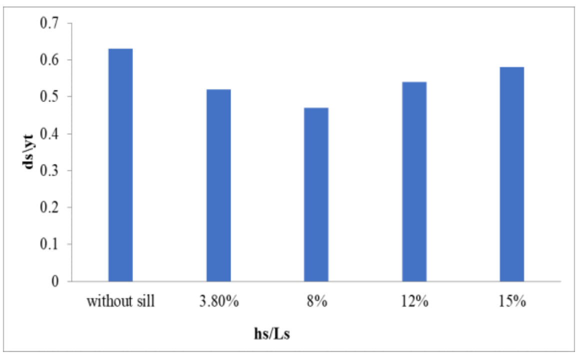

Fig. (10) The relation between maximum relative scour depth (d_s/y_t) and different relative sill height (h_s/L_s) at (F_t = 0.4) at a relative gate opening (a/L_s = 23%).

For previous results of all relative gate openings and relative sill heights, one can observe that the relative maximum scour depth increases with the increase of the gate opening in the absence of a sill. Also, in the case of a sill with a high relative height, the relative maximum scour depth increases from all gate openings. The relative sill height of 8% gives the minimum value of the maximum relative scour depth for all relative gate openings.

4.2. Contour maps of scour hole and scour profile

The contour maps of bed morphology were drawn by using **The Surfer program** [25]. Figures 11 to 15 show the contour map of bed morphology for a relative gate opening (a/L_s = 13%) at Tail Froude number (F_t = 0.4). It can be observed that at the relative sill height of (h_s/L_s = 8%), the scour and deposition values are minimum for the same condition.

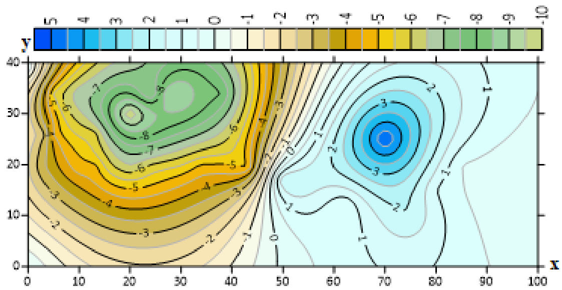

Fig.(11):Scour contour map for bed morphology for (h_s/L_s) = 0 (without sill) at F_t = 0.4

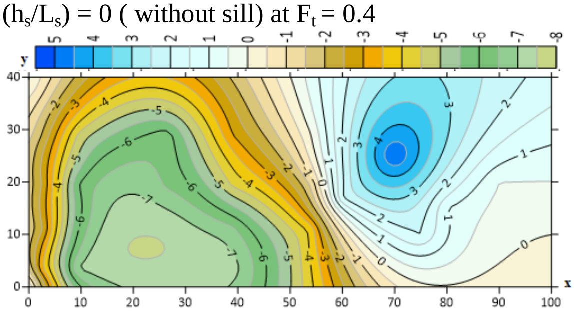

Fig.(12): Scour contour map for bed morphology for (h_s/L_s) =3.8% at F_t = 0.4

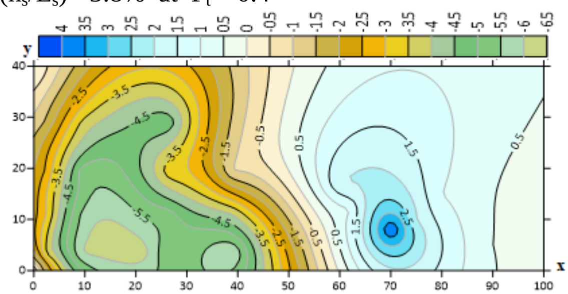

Fig.(13):Scour contour map for bed morphology for (h_s/L_s) = 8% at F_t = 0.4

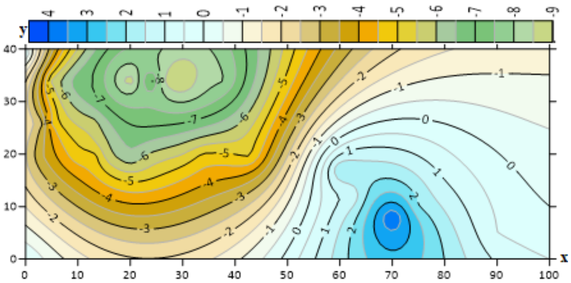

Fig. (14): Scour contour map for bed morphology for (h_s/L_s) =12% at F_t = 0.4

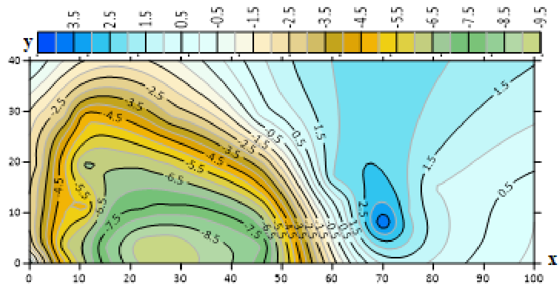

Fig. (15): Scour contour map for bed morphology for (h_s/L_s) = 15 % at F_t = 0.4

5. Statistical analysis

For each of the simulated scenarios, regression analysis was used to create a prediction model connecting the relative maximum scour depth to other independent variables. To develop a general equation that would describe all of the independent parameters, various experiments were conducted. The relative scour depth cannot be expressed by this equation's determination coefficient because it is so small. As a result, the following anticipated equations for several simulated models were developed:

$$\frac{d_s}{y_t} = 0.64F_t + 0.04\left(\frac{h_s}{L_s}\right) + 0.28\left(\frac{a}{L_s}\right) \qquad (6)$$

The determination coefficients = 94%, and stander errors = 0.07

Figure 16 Comparison of predicted values for the relative scour depth from Eq. (6) with measured data and Figure (17) clear the relation between Residuals and measured (d_s/y_t). It was found that the predicted equations express well the measured data.

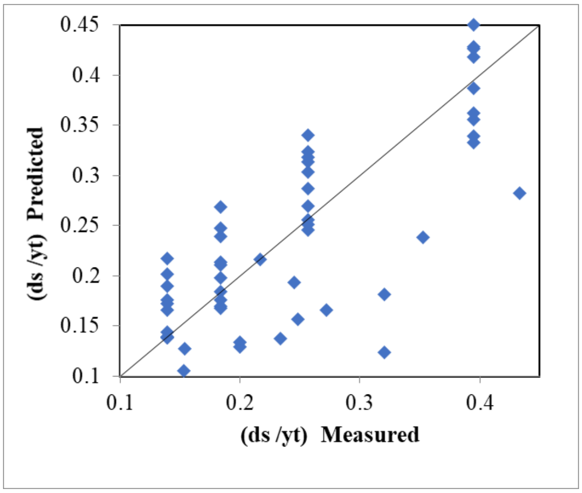

Fig. (16) Comparison of predicted values for the relative scour depth from Eq. (6) with measured data.

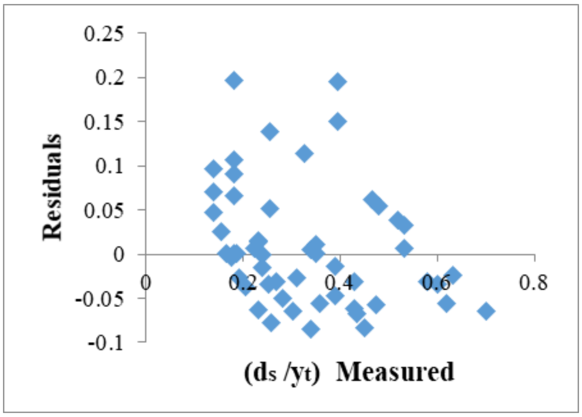

Fig. (17) The relation between Residuals and measured (d_s/y_t)

6. Comparison of measured data with other studies

Scour equations for downstream of the hydraulic structures for other researchers are available. For comparison purposes, some of these equations were used to calculate the maximum scour depths downstream hydraulic structures. Fig. (18) show a comparison between the experimental results for present study in cases of a relative gate opening (a/L_s = 13%) and each of Altinbilek (1973) and Chatterjee et al.(1994) [27]. It is observed that, the empirical of Novak (1961) and Altinbilek (1973) equation give higher values of (ds /yt) but Chatterjee et al.(1994) equation give very close values of the scour depth obtained from the present study as shown in Fig.(18). It can be said that, the experimental data for this case are acceptable compared to the equations collected from review.

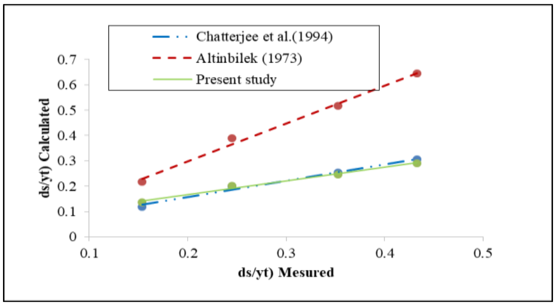

Fig.(18) The relationship between d_s/y_t) calculated and d_s/y_t) measured for present study with others studies.

7. Conclusions

The analyses and discussion of the results lead to the following conclusions:

- The effect of the sill height on the maximum scour depth downstream of the sluice gate was investigated experimentally.
- The maximum relative scour depth increases as the tail Froude number (Ft) increases.
- Increasing gate opening lead to decreasing relative scour depth in case without sill.
- The relative sill height of (h_s/L_s = 8%) reduces the maximum scour depth for different gate openings.
- The maximum relative scour depth rises with relative sill height (h_s/L_s) after (h_s/L_s) at 8%.
- Predicted equations, which agree well with the measured data, for relative scour depth are given as follows:

$$\frac{d_s}{y_t} = 0.64F_t + 0.04\left(\frac{h_s}{L_s}\right) + 0.28\left(\frac{a}{L_s}\right)$$

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