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Effect of local scour on Rod El Farag Cable Stayed Bridge Piers

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الملخص العربي
دراسة تأثير النحر الموضعي علي اساسات الكوبري المعلق بمحور روض الفرج في حالات مختلفة من التصرفات و مناسيب المياه. ودراسة توزيع التصرف حول جزيرة الوراق.

Abstract
Bridges are very important structures that could be considered as a strategic structure. Local scour is the most common cause of bridge collapse. It is removing bed particles from around bridge Supports because of many variables including continuous flow of water, mean velocity, flow depth, sediment particles size and the pier width. In this case study, the cable stayed bridge of Rod el Farag corridor connects the east branch to El Warraq island. This area is in the fourth reach of river Nile. Water discharge is a necessary variable in boundary conditions that is required in the scour calculation for this area. The water flow is distributed around El Warraq island. A one-dimension mathematical model HEC-RAS was used in preparing simulation to calculate the flow distribution ratio around the island. The same model was used in preparing simulation for the bridge area and calculating both local and contraction scour. Both simulations were calibrated by using a velocity measured data of the research area. Finally, the bridge supports were infected by scouring especially local scour. The pier number R3 will have the greatest local scour.

Keywords Local scour – Bridge piers – Contraction scour – Flow bifurcation – HEC-RAS

1 Introduction
Bridges are very important structures across ages. It connects a lot of places that have obstacles together. Rod El Farag Corridor is one of the most important projects in Egypt as it connects Cairo governorate with the Alexandria desert rood. This corridor crosses the Nile river in two intersections. One of these intersections is El Warraq – Shobra bridge which is cable stayed Bridge and that where the research point is. It is crossing the Nile river at km 10.5 downstream El Roda gauge station. Local scour is the most common bridge failure case in the last century. Water flow around bridge supports causes scour as it makes erosion in the surrounding area. Local scour is removing the soil particles from around bridge piers. Water stream flow create vortices when it clashes with an obstruction. These vortices affect directly on the pier base. These vortices are known as horseshoe vortex and wake vortex.

1.1 Objectives
Evaluate the effect of local scour on the bridge support and contraction scour on the bridge area by simulating different discharge and the corresponding water level on the research area.

1.2 Research plan

1. Collecting a literature review for related topics.
2. Gathering the field morphological and hydrological data for the study area.
3. Preparing one dimensional mathematical model to study the flow bifurcation and calibrating the model parameters.
4. Analyze the output data, preparing and calibrating one dimensional mathematical model to study the changes on the foundations at different scenarios.
5. Analyze the output data to study both local and contraction scour problems.
6. Summary and recommendation.

2 Literature review

In the former decades, a lot of researcher focused their work on scour problems. A lot of those researchers were keen to find a suitable formula to estimate the maximum scour in many field areas. Many of these equations were discussing the local scour around bridges supports.

2.1 Local scour

Local scour is the continuous decrease in bed levels that always happens around any obstacles in water like abutment and piers. Main cause of scour creation is the vortices creation. The horseshoe vortex could happen because of the accumulation of water on pier upstream surface. The amount of the sediment that could be removed by the vortices is greater than the amount that could be transported in the same area. This is a summarized description of the scour hole creation. The strong of horseshoe vortex is connected by the scour hole depth as it becomes weaker as long the scour hole depth increase (Richardson and Davis 2001). There is another type of vortex that could be created around the biers which called wake vortex. This type removes the bed particles downstream the bridge piers. Its intensity constringes quickly when the distance of the pier is increased downstream. That’s the reason of the deposition downstream of the long pier (Lagasse, et, 2009). There are many factors that could influence on bridge support’s local scour. These factors are flow depth and velocity, pier width and length if it was skewed with the flow direction, pier shape, bed material gradation and size.

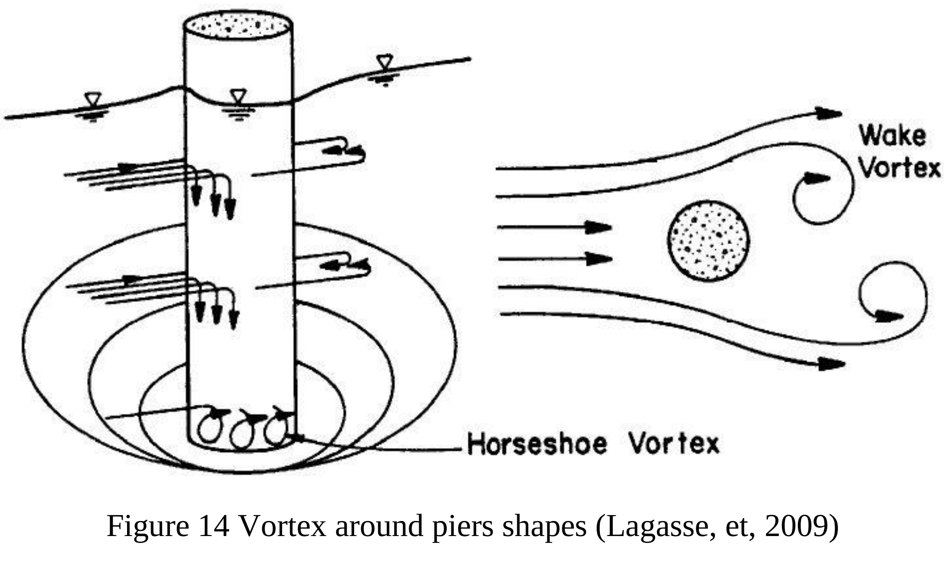


Figure 14 Vortex around piers shapes (Lagasse, et, 2009)

2.2 Contraction scour

This type of scour happens because of the reduction of channel cross section area as it was minimized by the bridge piers. This effects on the flow by increasing its velocity in cross section which increase shear stress and increase scour. It could be live bed or clear water (Abdellatef & Aboulata, n.d.).

2.2.1 Live bed

This could happen when the bed material upstream of the bridge could transport to the cross section of the bridge (Abdellatef & Aboulata, n.d.).

2.2.2 Clear water

This type could happen if the bed material upstream of the bridge could not transport to the bridge cross section. Also, it could happen if the bed particles upstream of the structure could transported through the channel downstream of the bridge cross section bridge (Abdellatef & Aboulata, n.d.).

2.3 CSU Equation and Froelich’s Equation

There are many equations that could calculate bridge supports local scour. HEC-RAS depends on two equations to calculate it. HEC-RAS recommends the equation of “Colorado State University” CSU equation to calculate local scour in HEC No.18 report (Richardson, 1990). It is the default equation in the program. This program was updated four times since its development in 1975 until now to be accurate in its results. This equation is suitable in predicting with scour depth. The other equation in HEC-RAS is dr. David Froehlich equation which was developed in 1991. This equation is not recommended by HEC-RAS. It was illustrated in the program for comparison only. It always gives unreal results as it gives results lower than reality (Mousavi & Daneshfaraz, 2013).

2.4 Previous studies in local scour at bridges

There are many researches in local scour calculation techniques.

(Hager & Unger, 2010) studied the effect of flood on pier scour. They illustrated this case in both the experimental and theoretical approaches. They studied the experiment as a clear water scour and a non-uniform sediment. The experiment was defined by velocity, group of cylinder bridge piers, flood hydrograph.

(Sheppard et al, 2014) used twenty-three equation that could calculate local scour in cohesionless sediment. He used field data and applied it in laboratory. He measured the quality of the used data and rejected the incorrect data. He couldn’t measure the scour hole in the measurement time as it wasn’t been created yet. By comparing between the scour equation, the valid equations were reduced to seventeen equation.

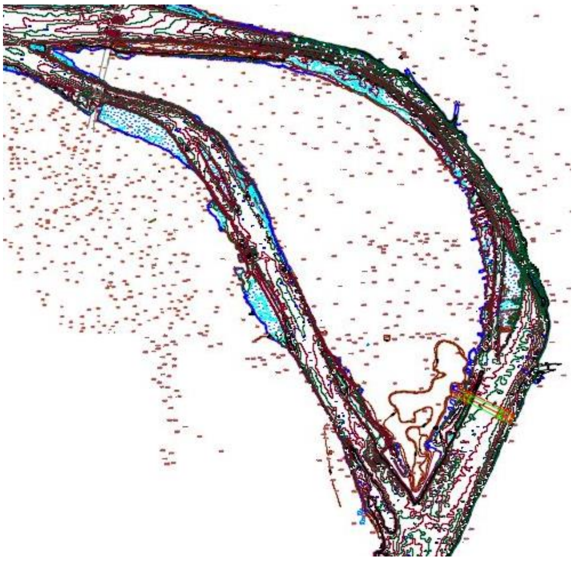
(Melville, 1975) measured flow magnitude, direction and calculated scour holes around circular piers. He deduced that flow upstream the pier gets his way downward creating a horseshoe vortex. This vortex size and circulation increase rapidly. If the scour hole was expanded, the velocity was decreased at the bottom. After that the vortex intensity could be decreased to reach to the equilibrium stage.

3 Data collections

Model preparation needs varies kinds of data in different times. These data could be classified to topographic data, hydrographic data, velocity data, bed material samples and bridge data.

3.1 Hydrographic data

Nile Research Institute “NRI”, had carried out a hydrographic survey in the study area in 2003 and also in 2010. In 2003 NRI had surveyed all the area around the island between the two banks of the river and also downstream and upstream of the island. They made about 160 cross sections in the area of study as the spacing between cross sections was equal 50 m. these sections were used to produce contour map see figure 2 In 2010 NRI only surveyed the area around the bridge. They only surveyed 21 section as the spacing between these cross sections was equal 50 m see figure 3. The plan coordination was measured by using differential GPS system which has a global sub meter accuracy. while the depths were measured in the same time by using echo-sounder system which has a relative accuracy +/- 5 cm. Also, the shallow areas where depths were lower than half meter were surveyed by using the total station system. Furthermore, technician teams were executing the land survey by using different portable GPS system. They used post processing system in collecting data. Finally, all of the mentioned three data were applied in producing the hydrographic contour maps which used in studying river bifurcation (flow distribution) and studying the local scour on bridge supports.



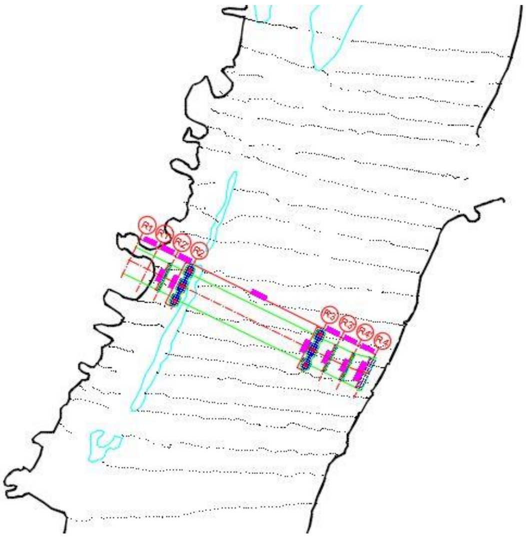


Figure 15 Contour map of the study area – 2003   Figure 16 Hydrographic survey of the study area – 2010

To do any hydraulic research the daily water discharge and the corresponding water level are needed. That’s why Ministry of Irrigation and Water Resources measures the passing discharge through barrages and the upstream and the downstream water level. Also, it has a different gauge station across the Nile to measure water levels. In this research a daily discharge and water level for the time of the hydrographic survey was used in calibrating model as illustrated in figure 4 and figure 5. In addition of this, the maximum discharge and the corresponding water level was used in the local scour study as illustrated in figure 6 and figure 7.

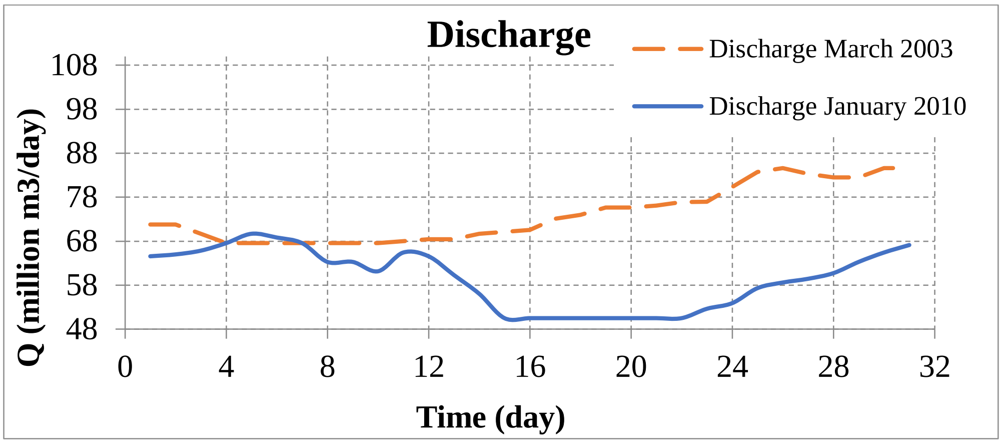


Figure 17 River Nile discharge for the study area

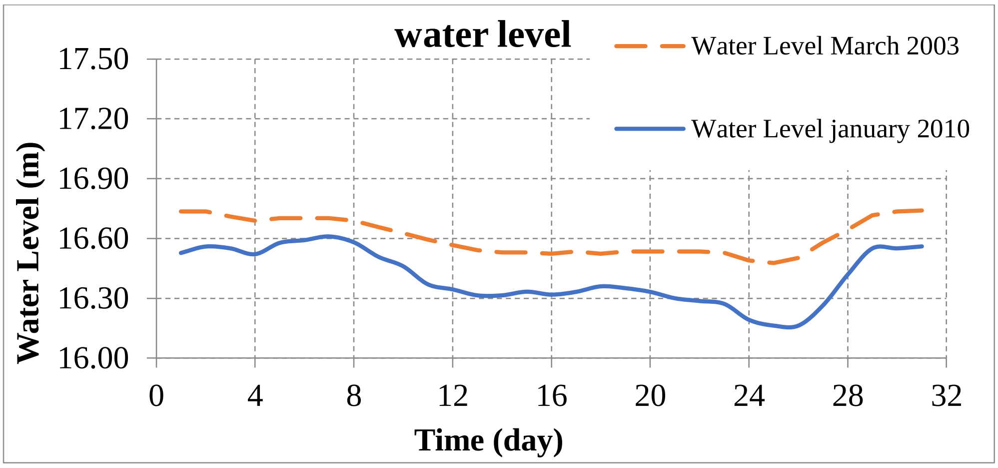


Figure 18 River Nile hydrograph for the study area

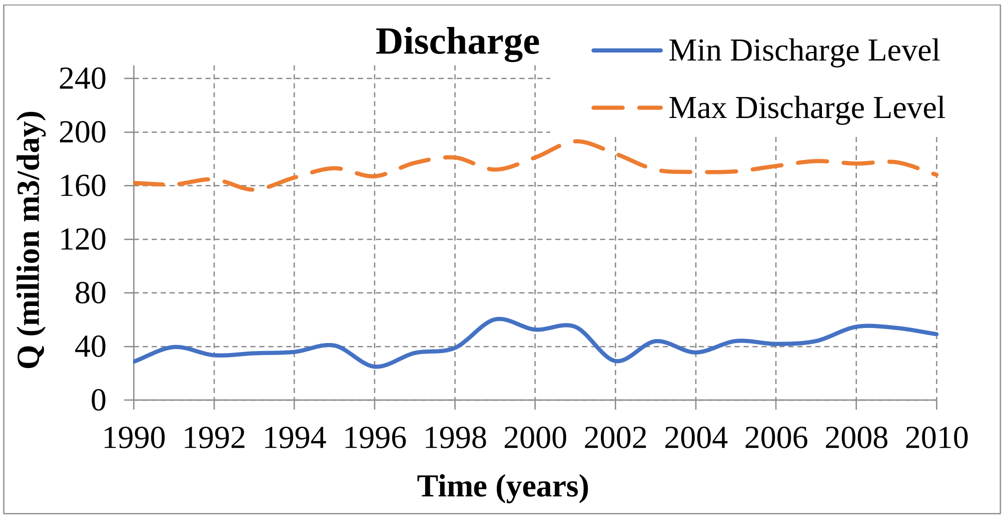


Figure 19 River Nile max. and mini. discharge at the study area

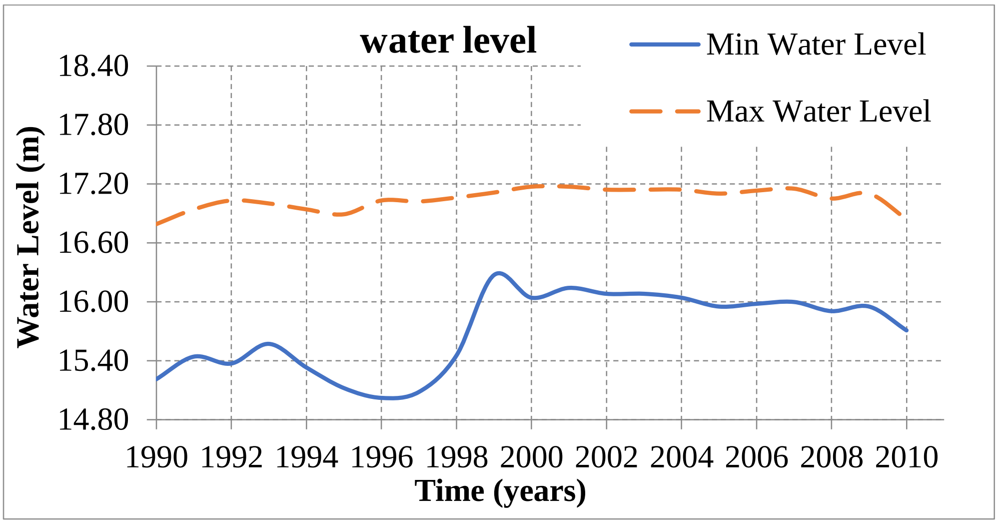
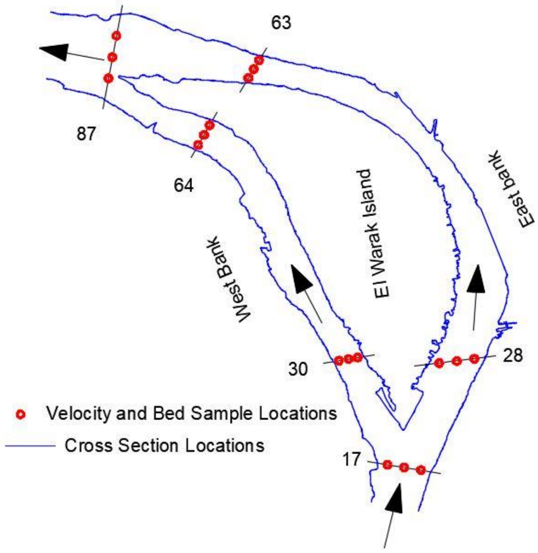


Figure 20 River Nile maximum and mini water level for the study area

The flow velocity was measured in both 20th march 2003 and in 5th January 2010. In 2003, Velocity of six cross sections were measured in the study area see figure 8. Also, in 2010, Three cross sections velocity were measured in the study area see figure 9. For each section, the stream flow velocity was measured in three different location east, middle and west. In every location, velocity was measured in several depths. These depths were under the water surfaces with 0.5 m and above the river bed with 0.75 m and at 25%, 50% and 75% of the total depth. In general, the stream flow velocity is affected with the boundary roughness. The flow velocity in the channel's center is faster than the flow near the ground surface.



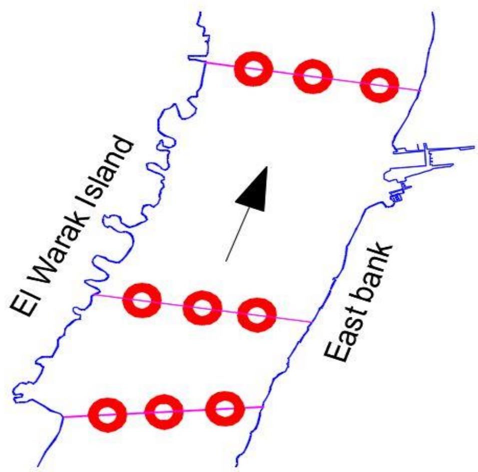


Figure 21 velocity and bed sample location 2003

Figure 22 velocity and bed sample location 2010

Table 1 Velocity data

2003		2010	
SEC	Mean Velocity	SEC	Mean Velocity
17	0.23	1	0.32
28	0.33	7	0.27
30	0.25	21	0.26
63	0.47		
64	0.23		
87	0.29		

3.2 Bridge Data

This bridge is one of Rod el Farag corridor intersections. It was designed by “Arab Consulting Engineers Moharram – Bakhoum” under the supervision of the aramid forces engineering consultant. This bridge has seven vents see figure 10 (ACE, 2010). The deck width is 60.40 m. The foundation data is illustrated in table 2. The bridge centerline is skew on the flow line with angle equal 88°. In all piers, the pile cap elevation is above the maximum water level. The piles in R2’, R3’, R4’ are staggered. Also, the piles diameter is varied from one pier to another.

Table 2 the foundation data

Axis	**Width**	**Length**	**Pile Diameter**
	m	**m**	**m**
R2'	4.5	60.4	1.5
R2	19	94	2
R3	19	94	2
R3'	4.5	60.4	1.5
R4'	4.5	60.4	1.5
R4	12.5	67.855	1

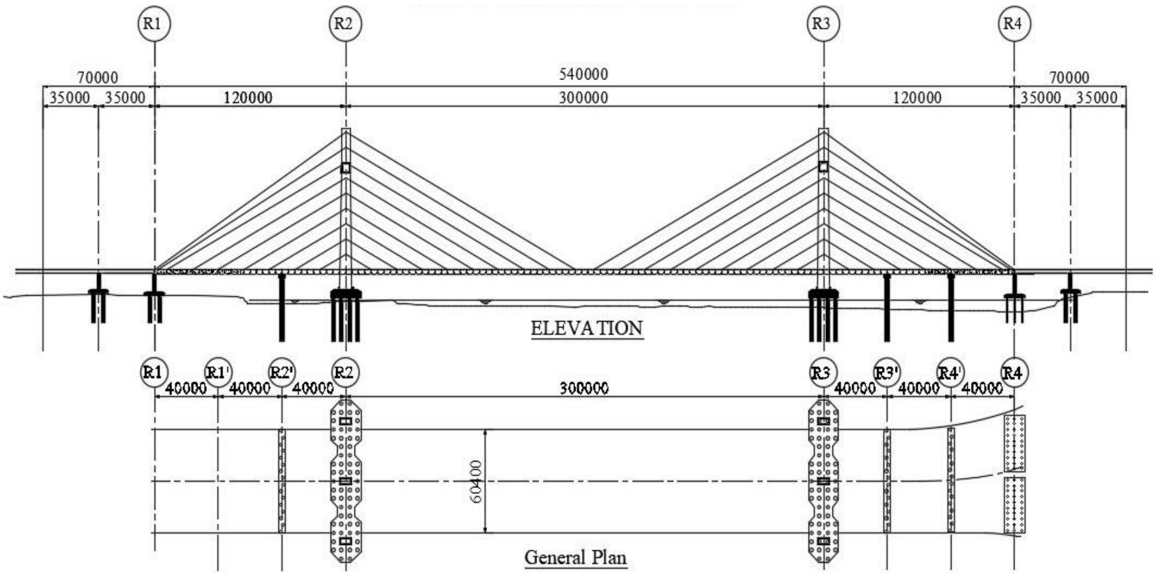


Figure 23 The bridge plan and elevation

4 Model

To simulate any physical phenomena, we need to make either physical model or mathematical model. The mathematical model is the most widely applied techniques in modelling (Samir, Saad, & By, 2010). To simulate this research the “Hydraulic Engineering Center’s River Analysis System” HEC-RAS was used. This software could be used in simulating one-dimension modelling and also two-dimension modelling. It should be mentioned that the 2D modelling in HEC-RAS has current limitations such as the bridge capability model couldn’t be used inside a 2D flow area (Brunner, 2016). Based on that HEC-RAS 1D model was used. The results accuracy is depending on the quality of the topographic, the hydrologic, the velocity and the bed roughness data.

4.1 River Bifurcation Model

The study area is in the east branch of the Nile as El Waraq island separate the River in Km 9 downstream El Roda gauge to east branch and west branch. This called river bifurcation. This island ends in km 17 downstream El Roda gauge where the two branches of the Nile merges again. As a result, the main discharge in the river will be distributed around the island. This research area is in the east branch. So, the flow bifurcation should be calculated.

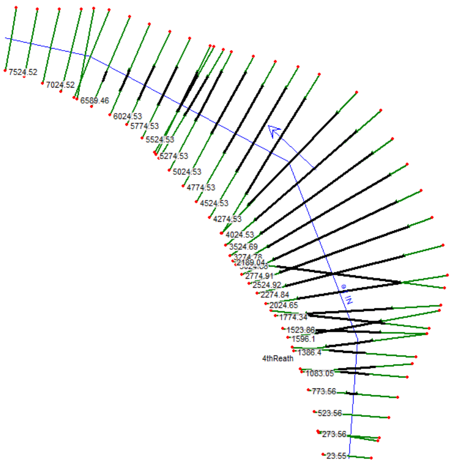


Figure 24 Cross sections in HEC-RAS

To simulate bifurcation model in HEC-RAS, the user should prepare the cross section from the east bank of river to the west bank of river as it had to contain the island topography. The island should be defined as blocked obstructions. In this research the spaces between cross section is 250 m. Beside adding some of real cross section where the field group measured flow velocity as shone in figure 11. These cross sections were applied to calibrate this model.

4.1.1 River bifurcation model calibration

To calibrate model, a parameter should be measured in field and modify the model parameters until it results the approximately same field result. To calibrate this model, the field group measured six cross section flow velocity. Two of them are located in main channel and the other four are in left branch and right branch. Manning coefficient is a parameter which could strongly modify model results. Its adjustment must be made carefully as it should be according to size and type of bed and bank material. To get the highest agreement between the calculated results and the measured results, the user should run several models. Manning coefficient was modified in these models until the mean velocity was calibrated see figures 12, 13, 14.

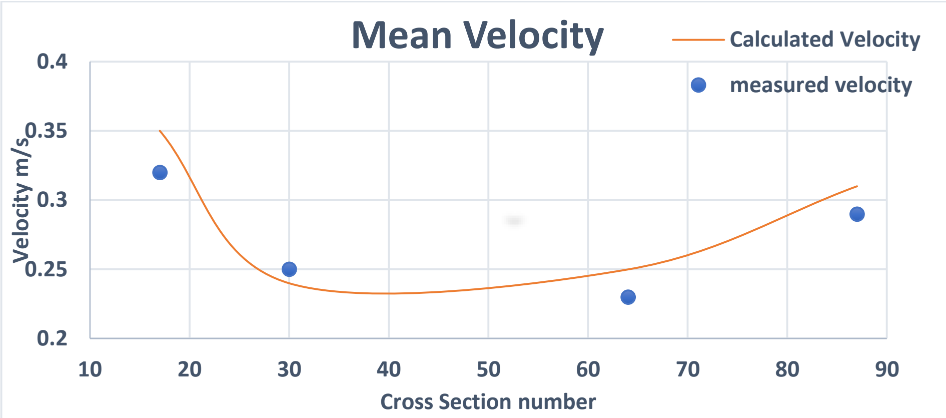


Figure 25 Velocity in main river and left branch

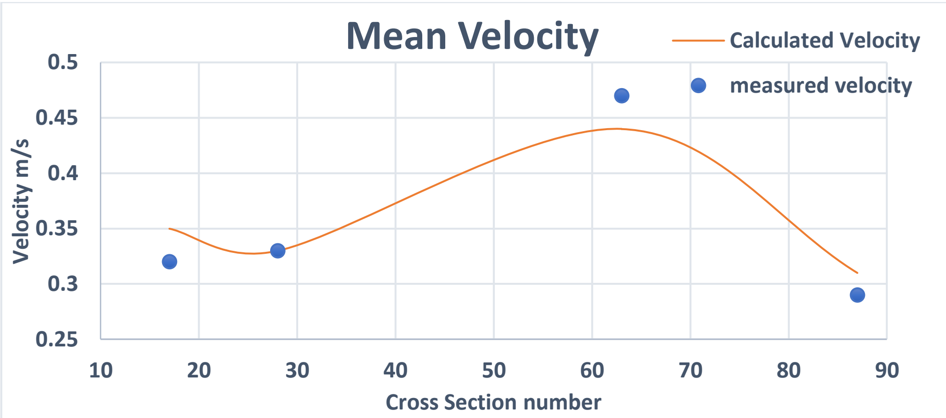


Figure 26 Velocity in main river and right branch

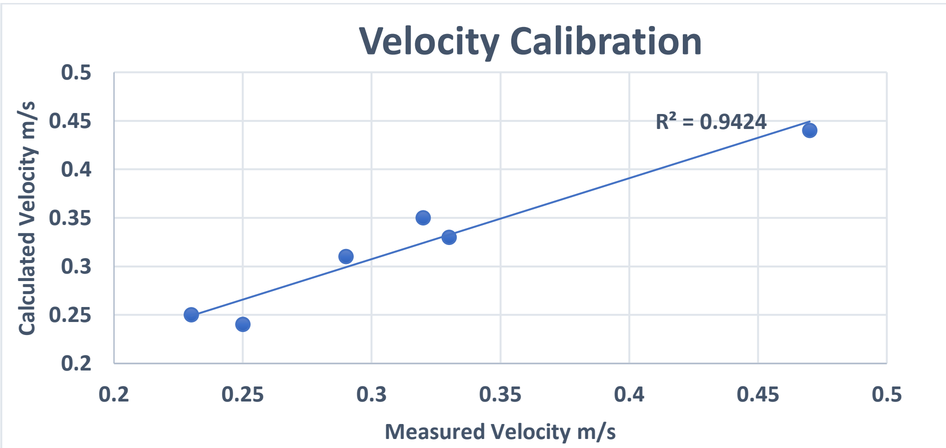


Figure 27 Quality of the velocity calibration

4.1.2 River bifurcation model results

After model calibration, the ration of flow discharge should be calculated. HEC-RAS measures discharge in every cross section. Four cross section was studied to compute the ratio between discharge in the right branch and in the main channel. After analyzing the four cross sections the mean right branch discharge ratio is 70.78% of the main discharge. This ratio could be applied to distribute the flow discharge around El Warraq island.

4.2 The Bridge Model

This model was prepared to study the area of the bridge area as presented in figure 15. The cross section spacing is vary in this model. The bridge area the cross sections spacing was .5 m for 200m long around the bridge. The other area cross sections spacing was 2.5 m. the first 250 m and the final 170 m of study area loos like triangle. the spacing between cross sections in these areas varies between 10 m and 14 m. the bridge model was applied in two stages. The first stage was model calibration. The second stage was bridge model and scour analysis.

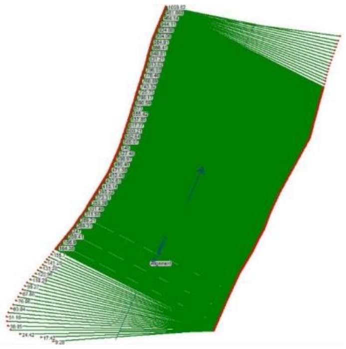


Figure 28 The bridge model study area

4.2.1 The bridge model calibration

To calibrate this model, three cross section flow velocity were measured by the field team. This data was discussed before in table 1. Manning number was adjusted to calibrate this model. Calculated and measured velocity are illustrated in figure 16. Also, quality of the velocity calibration is illustrated in figure 17.

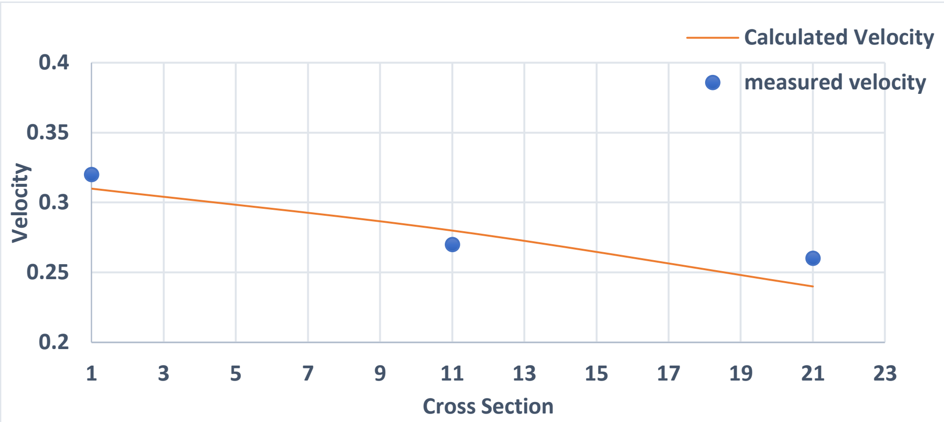


Figure 29 Velocity bridge area

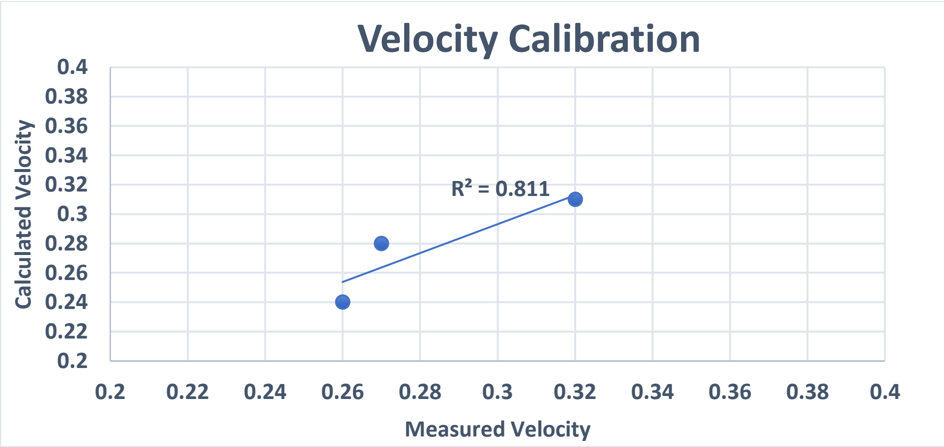


Figure 30 Quality of the velocity calibration

5 Scenarios

After calibrating the research area model, the bridge geometry data should be defined in HEC-RAS model. A lot of boundary conditions such as discharges and corresponding water level were taken to compute scour in this area. This boundary conditions are illustrated in table 3. One of the most important boundary conditions in designing hydraulic structures is the future discharge. This discharge is calculated from flood records of the Ministry of Water Resources and Irrigation before the construction of AHD. The corresponding water level of the future discharge was calculated by Nile Research Institute staff. They built a HEC-RAS one dimensional model and calculated the water level for every kilometer of river Nile (NRI, 2010).

Table 3 Boundary conditions states

Flow State	Discharge Million m3/day	Discharge m3/sec	Water Level
Minimum	25	203.82	15.02
Most Common	116.5	949.78	16.48
Maximum	193.100	1574.27	17.17
Future	350	2853.41	17.35

To study the local scour at the research area two scenarios should be studied in the varies discharge states. These scenarios are the pier shape as the real state is group of cylinders. Also, it could be rounded edge pier as spaces between the piles could be blocked by plants and rubbish. These scenarios will be illustrated in the following subtitles.

6 Local scour Analysis

Local scour depends on a lot of parameters. These parameters are illustrated in CSU equation which illustrated in equation 5-1 (USACE 2016). These parameters are flow depth, pier nose shape, angle of attack, bed shape, pier width, length of pier and mean velocity.

$$\boldsymbol{Y_s = 2Y_1K_1K_2K_3Fr_1^{0.43}\left(\frac{a}{Y_1}\right)^{0.65}}$$

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Where:

Y_s is Scour depth (m).

Y_1 is Flow depth upstream of support (m).

K_1 is pier nose shape correction factor.

K_2 is angle of attack correction factor.

K_3 is bed condition correction factor.

a is pier width (m).

Fr_1 is Froude number upstream piers = $\frac{v_1}{\sqrt{gy_1}}$

V_1 is flow mean velocity upstream piers (m/s).

g is acceleration of gravity (9.81m/s^2).

6.1 Group of cylinder piers scenario

The local scour was calculated by using HEC-RAS 1D which uses CSU equation to calculate local scour. In case of group of cylinders, the pier width should be considered as sum of non-overlapping projected widths of piles. These calculations are shown in table 4. The relationships between discharge conditions and local scour depths are illustrated in figure 18. The final results illustrated that the maximum scour always occurs at R3.

Table 4 Model results and its parameters in case of group of cylinder piers scenario

flow condition	Parameters	R2'	R2	R3	R3'	R4'	R4
common in all flow states	K1	1.00	1.00	1.00	1.00	1.00	1.00
	K2	1.25	1.25	1.25	1.25	1.25	1.25
	K3	1.10	1.10	1.10	1.10	1.10	1.10
	a	2.50	8.00	8.00	2.50	2.50	3.00
	L	60.4	94.0	94.0	60.4	60.4	67.86
	θ	2.00	2.00	2.00	2.00	2.00	2.00
minimum flow condition	y1	0.79	0.38	3.39	4.46	5.01	5.62
	Fr1	0.05	0.07	0.03	0.02	0.02	0.02
	V1	0.14	0.14	0.14	0.14	0.14	0.14
	ys	1.29	2.48	3.34	1.63	1.65	1.89
the most common flow condition	y1	2.26	1.85	4.86	5.94	6.49	7.09
	Fr1	0.09	0.10	0.06	0.06	0.06	0.05
	V1	0.44	0.44	0.44	0.44	0.44	0.44
	ys	2.40	4.97	5.66	2.73	2.76	3.15
maximum flow condition	y1	2.96	2.56	5.56	6.64	7.19	7.79
	Fr1	0.12	0.12	0.08	0.08	0.07	0.07
	V1	0.62	0.62	0.62	0.62	0.62	0.62
	ys	2.89	6.03	6.70	3.22	3.26	3.71
future flow condition	y1	3.19	2.79	5.80	6.87	7.42	8.03
	Fr1	0.19	0.21	0.14	0.13	0.13	0.12
	V1	1.08	1.08	1.08	1.08	1.08	1.08
	ys	3.69	7.72	8.52	4.10	4.14	4.71

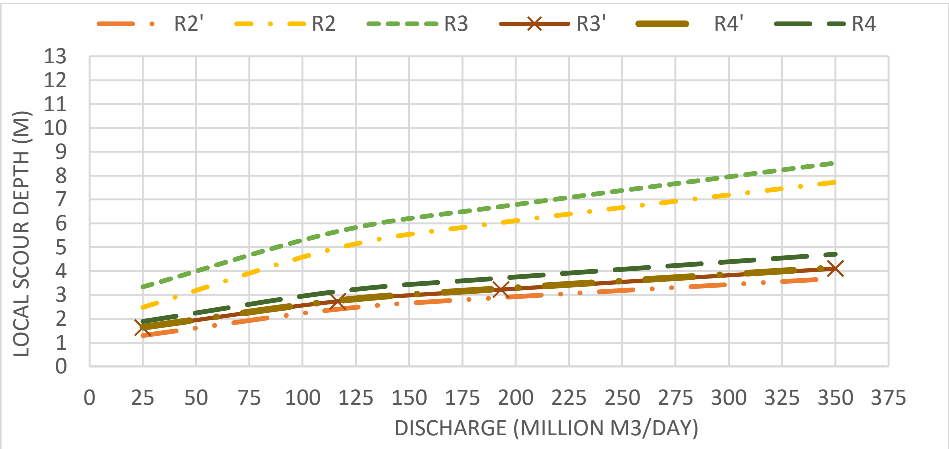

Figure 31 Relationship between discharge and local scour on bridge supports in case of group of cylinder piers scenario

6.2 Rounded nose pier scenario

This scenario could happen in case of blocking the spaces between piles in piers. The dimension of piers should be taken the outer spaces of piles and the outer nose will be rounded with the piles see figure 19. The results of this scenario are presented in table 5. The relationships between local scour depths at this scenario and discharge conditions are illustrated in figure 20.

Figure 32 Plan of the rounded nose piers

Table 5 Model results and its parameters in case of rounded nose piers scenario

flow condition	Parameters	R2'	R2	R3	R3'	R4'	R4
common in all flow states	K1	1.00	1.00	1.00	1.00	1.00	1.00
	K2	1.25	1.12	1.12	1.25	1.25	1.18
	K3	1.10	1.10	1.10	1.10	1.10	1.10
	a	2.50	17.00	17.00	2.50	2.50	10.50
	L	60.4	94.0	94.0	60.4	60.4	67.86
	θ	2.00	2.00	2.00	2.00	2.00	2.00
minimum flow condition	y1	0.79	0.38	3.39	4.46	5.01	5.62
	Fr1	0.05	0.07	0.03	0.02	0.02	0.02
	V1	0.14	0.14	0.14	0.14	0.14	0.14
	ys	1.29	3.63	4.88	1.63	1.65	4.02
the most common flow condition	y1	2.26	1.85	4.86	5.94	6.49	7.09
	Fr1	0.09	0.10	0.06	0.06	0.06	0.05
	V1	0.44	0.44	0.44	0.44	0.44	0.44
	ys	2.40	7.26	8.27	2.73	2.76	6.71
maximum flow condition	y1	2.96	2.56	5.56	6.64	7.19	7.79
	Fr1	0.12	0.12	0.08	0.08	0.07	0.07
	V1	0.62	0.62	0.62	0.62	0.62	0.62
	ys	2.89	8.82	9.80	3.22	3.26	7.90
future flow condition	y1	3.19	2.79	5.80	6.87	7.42	8.03
	Fr1	0.19	0.21	0.14	0.13	0.13	0.12
	V1	1.08	1.08	1.08	1.08	1.08	1.08
	ys	3.69	11.29	12.47	4.10	4.14	10.03

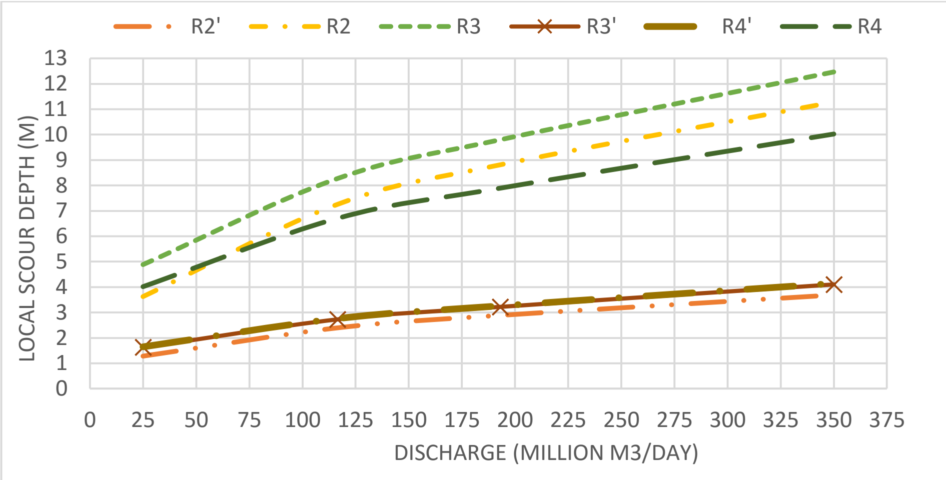

Figure 33 Relationship between discharge and local scour on bridge supports in case of rounded nose pier scenario

7 Conclusions

Based on this research, the following conclusions were concluded:

1. The mathematical model HEC-RAS that was used in this research could be used in similar studies.
2. The flow in the right branch of the Nile river around El Warraq island is greater than the left branch.
3. The maximum local scour was predicted to be in R3 pier as this pier is one of the biggest piers of the bridge and it is located approximately in the third of the cross section.
4. The flow condition affects directly on the scour depth as when the discharge increased the scour depth increased and vice versa.
5. The behavior of the supports affects directly on the scour depths as the scour depths in the rounded edge pier scenario is greater than the group of cylinder piers scenario.

8 Recommendations

1. The spaces between piles should be always clear of plants and rubbish as this will prevent the rounded pier nose scenario from happening.
2. Removing any construction material or any supports that was used in constructing the bridge from the river.
3. The designer of the cable stayed bridge of Rod el Farag corridor take local scour depth in the consideration when he designs future bridges.
4. The research area should be regularly monitored and revised by the bridge designer specially after floods.
5. Future researches should focus on applying a scour countermeasure system for this area.

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