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Investigations on the Impact of Using Elliptic Groynes on the Flow in Open Channels

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ABSTRACT

This paper presents a numerical simulation of the flow around elliptic groynes by using CFD software. The flow was simulated in a flume with 4m long, 0.4m wide, and 0.175m high with a constant bed slope. Moreover, the first Groyne placed at 1m from the flow inlet with a constant the Groyne height of 10*cm* and a 1cm thickness, and the width of Groynes equals 7*cm*. A submergence ratio of the elliptic Groynes of 75% was assumed, corresponding to a discharge of 0.0057m^3/sec. The CFD model showed a good ability to simulate the flow around Groynes with good accuracy. The results of CFD software showed that when using double elliptic Groynes, the bed shear stress is decreased with the increase in the spacing between Groynes, as well as and the best spacing between the double elliptic Groynes is twice of the Groyne width. Moreover, the used number of Groynes has no much impact on velocity and shear stress values.

Keywords: Groynes, CFD, SST, river-banks protection.

تحري حول تأثير استخدام السنون الحجرية ذات شكل القطع الناقص على الجريان في القنوات المفتوحة

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الخلاصة

يعرض هذا البحث المحاكاة العددية للجريان حول السنون الحجرية ذات شكل القطع الناقص باستخدام برنامج CFD. أجريت محاكاة الجريان في قناة بطول 4م وعرضها 0.4 م وأرتفاعها 0.175 م مع منحدر ثابت للقاع. علاوة على ذلك تم وضع أول سن حجري على بعد 1 م من مدخل التدفق مع أرتفاع ثابت هو 10 سم وسمك ثابت هو 1 سم ، وكذلك عرض ثابت للسنون الحجرية يساوي 7 سم. تم أفتراض نسبة الغمر للسنون الحجرية ذات القطع الناقص مساوية لـ75% والتي تتوافق مع تصريف 0.0057 م3/ثانية. أظهر نموذج CFD قدرة جيدة على محاكاة الجريان حول السنون الحجرية وبدقة جيدة. أظهرت نتائج برنامج CFD ،أنه عند أستخدام السنون الحجرية المزدوجة ذات شكل القطع الناقص يقل إجهاد القص عند القاع مع زيادة المسافة بين السنون الحجرية وكذلك أفضل مسافة تباعد بين السنون الحجرية المزدوجة ذات شكل القطع الناقص هي ضعف عرض السن الحجري. علاوة على ذلك إن العدد المستخدم من السنون الحجرية ليس لها تأثير كبير على قيم السرعة وإجهاد القص.

الكلمات الرئيسية: السنون الحجرية، SST,CFD, حماية ضفاف الأنهار.

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1. INTRODUCTION

Many techniques exist to protect river banks against erosion, such as vegetation, gabions, concrete mattresses, soil-cement, etc. However, groynes have been used to protect riverbank and flow-control because it is better economically, environmentally, and extra benefits. The groynes are a rigid structure extended from a bank of the river to interrupts flow and limit the scour resulted from high flow velocity. Groyne shape, degree of permeability, length, orientation, a number used, and spacing are design parameters of the protection against scouring by using the Groyne. These parameters play an important role in controlling and driving the flow to the desired direction to protect the riverbanks and damage the hydraulic structure.
(Al-Khateeb, et al., 2016) carried out an experimental study to evaluate a local scour about two shapes of non-submerged curved groynes. A quadrant and semi-parabolic shape of impermeable groynes were created with different parameters such as groyne length, groyne numbers, the spacing between them, and various discharges. The results show the depth of scouring decreased by decreasing the groyne length and the spacing between groynes. Generally, the scour is reduced by nearly 75% in quadrant groynes as compared with the semi-parabolic groyne. **(Ibrahim and AL-Thamiry, 2018)** conducted experiments for local scour about semi-parabolic and elliptic groynes in a laboratory flume with various parameters. The results of scour depth were compared with other researches about straight, T-head, L-head, parabolic, and quadrant shapes of the groyne. Generally, the elliptic groyne is the best case of all groynes because it gives minimum scour depth, a minimum volume of scour, and transition of sediments, unlike the semi-parabolic Groyne and other shapes. **(Koutrouveli, et al., 2018)** studied numerically a groyne spacing role on the effective control of wall shear stress in open-channel flow. ANSYS Fluent, the shear-stress transport, SST(k-ω) model was used, and it was validated versus experimental data for the situation of a single straight groyne. The results showed a numerical model was predicted to the flow circulation correctly in the corner between the groyne downstream and the channel sidewall. This is due to the excellent predictive ability of the separation of flow by the SST k-ω model. **(Abbas and Khassaf, 2019)** conducted an experimental local scour evaluation about non-submerged S-head groynes with various parameters. The results show the maximum depth of scouring was observed at groyne upstream. Moreover, the depth of scouring was increased with increase Froude number, flow velocity, and flow depth. While it was decreased with increasing the groyne number and the spacing between them within the study limits. One common erosion problem in rivers in Iraq is located at the Shatt al-Arab River. Therefore, **(Abbas and Mohammed, 2020)** studied roughness impact numerically on velocity variations in the Shatt al-Arab river's selected reach to reduce erosion. The results proved the impact of the increased bed roughness on the velocity variations and location of the maximum velocity by driving it to the other side. Furthermore, **(Daham and Abed, 2020)** simulated numerically 1D and 2D flow to reach Al-Gharraf river's reach by using HEC-RAS software. The hydraulic characteristics of the unsteady flow specify in Al-Gharraf river to define the locations facing problems of erosion and sedimentation and recommend the important treatments. The simulation results of the 2D model were more perfect than their corresponding 1D model, resulting in more agreement of these values with values of measured. There are many other applications of the CFD software in the open channel flow. **(Kadhim and AL-Thamiry, 2020)** studied the behavior of flow around intakes of vertical pumps to calculate critical submergence depth to avoid vortices that formed at a flow surface. The SST(k-w) model has been used in ANSYS Fluent to simulate flow at intakes of pumps. Moreover, the validation of this model has given good results compared with the results of published laboratory experiments. Computational Fluid Dynamics, CFD, has become an effective tool to study the hydrodynamic of open channels under different conditions with comprehensive details rather than relying on conducting time-

consuming and costly field or laboratory experiments. This paper aimed to make used of published laboratory experiments data on curved groynes to validate the CFD software. The flow model will then be created by this software to conduct investigations on the impact of using this type on the flow's hydrodynamics.

2. DESCRIPTION OF THE INVESTIGATED MODELS

Elliptic groynes models are investigated under different design parameters. These parameters significantly control and drive the flow to the required direction to protect the riverbanks and damage the hydraulic structure. The design parameters that are included in this investigation are length, Lg, width, Wg, number of groynes, N, and spacing between them, b.

Generally, published data of laboratory experiments on elliptic groynes were carried out by **(Ibrahim and AL-Thumairy, 2018),** where the validation was done by the use of the CFD Software. Four cases were of these data were used in validation runs of the CFD software. The parameters included in these cases are the groyne width, Wg= 13*cm*, groyne length, Lg=20*cm*, numbers of groynes (single or double), spacing, 1Wg, 1.5Wg, 2Wg, and 2.5Wg. The flume that was used in these experiments is of 4*m* long, 0.4*m* wide, and 0.1*m* deep with a slope of bed equal to zero. Elliptic groyne has of 1*cm* thickness and 10cm height.

The set of new investigations on the simulated flow around elliptic groynes was under a projection of Wg=7*cm* and Lg=10*cm*. The parameters that were applied in this set are the used number of groynes, N =1, 2, 3, 4, 5, and a constant spacing between them equal to 2Wg. It is simulated under a constant discharge of 0.0057m^3/s more than the experiment discharge that corresponds to the submergence of the elliptic groynes of 75%. **Fig.1** shows the flume's geometry that was used in the simulation runs and the location of the first groyne from the flow inlet. The first groyne is located at 1*m* from the flow inlet with a constant groyne height of 10*cm* and a 1*cm* thickness.

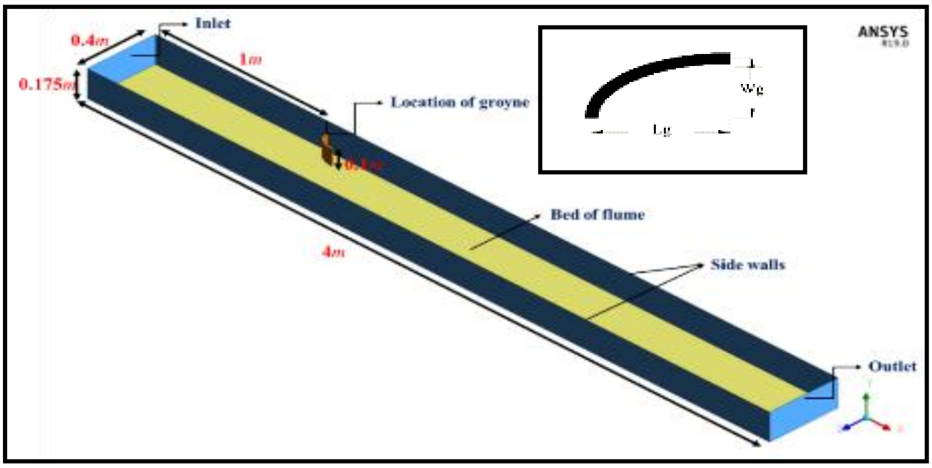


Figure 1. The geometry of an open channel with the location of the first groyne.

3. DESCRIPTION OF CFD RUNS

A commercial software package, ANSYS Fluent, was used to simulate flow around groynes. The governing equations of the three-dimensional flow of incompressible fluid are the continuity and the Navier-Stokes equations. It uses the Finite Volume Method, FVM, to solve these equations **(Versteeg and Malalasekera, 2007)**.

ANSYS workbench has a meshing tool. The meshing of the whole model is done separately. Assembly meshing method tetrahedrons, relevance center is fine, high was selected for smoothing

quality, proximity and curvature has chosen for advanced size function. The minimum and maximum cell size are then changed until getting the best quality of the meshing. Tetrahedrons are similar to Pyramids, but the base is triangular. According to the geometry, the meshing tool chooses the best distributions for minimum and maximum of elements size according to the geometry, as shown in **Fig.2**. Mesh metrics of quality are skewness and orthogonal, according to CFD. The maximum value of skewness is ranging between 0.79 - 0.82, i.e., acceptable to good quality. While the minimum value of orthogonal is extending between 0.22 - 0.25, i.e., always a good quality for various configurations. Element numbers of tetrahedrons are ranging between 1600000-1900000, depending on the different configurations.
Two models were used in this study, the multiphase and the viscous turbulence model. The multiphase selections are volume of fluid, VOF, open channel flow, implicit and implicit body force. The turbulence model uses Shear Stress Transport, (SST) k-ω, which has previously proven strength and accuracy to a simulation of flow around groynes. Multiphases are using air and water under standard temperature. Two-phase are air as a primary phase, and water is a second phase with surface tension constant equal to 0.072*N/m*.

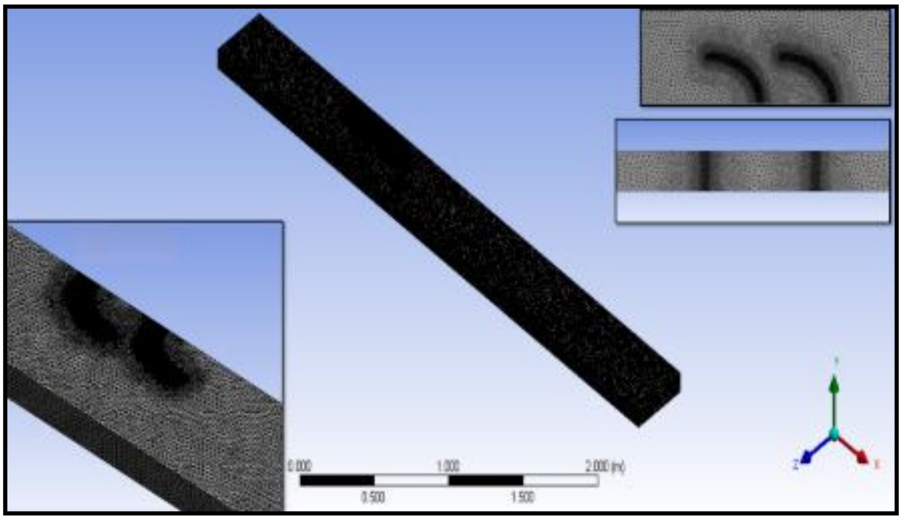


Figure 2. The meshing of geometry by using a meshing tool of ANSYS Fluent.

Mainly, discharge at the inlet and water depth at the outlet are adopted boundary conditions. There is a set of hydraulic parameters as input, such as the free surface and bottom levels, turbulence intensity, and hydraulic diameter for inlet and outlet boundary conditions. The bed of the flume and sidewalls boundaries is a wall with no-slip and wall shear stress equals zero, except for the bed, it was a roughness height that equals to, d_{50}=0.7*mm*, as shown in **User's Guide, Release 19.0**. Operating conditions are atmospheric pressure. Gravitational acceleration is -9.81m/s^2 for the Y-axis and specified operating density equal to air density i.e. the lower of the two-phase density. To complete the CFD modelling description, pressure-velocity coupling, the PISO scheme segregated algorithm was used. Second-order upwind has been used for the momentum, turbulent kinetic energy, TKE, and specific dissipation rate.
Table 1. Shows The hydraulic information for validation and a new investigation of the elliptic groynes. Firstly, simulating open channel flow without groynes with a new discharge. Then, open channel flow around the elliptic groynes is simulated with other investigations.

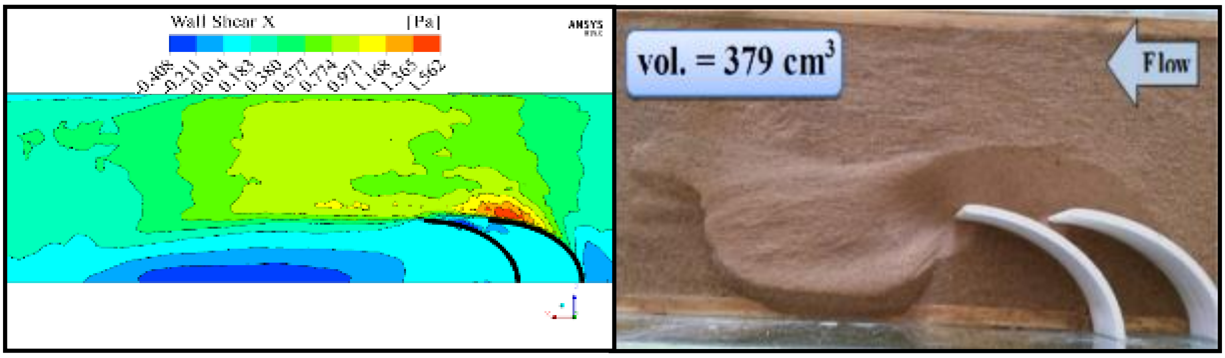
Table 1. The hydraulic information for validation and a new investigation of the elliptic groynes.

N.O.	**y**, *cm*	**Q**, m^3/s	**Fr**	**DH**, *m*	**Re**	**T.I%**	**Q**, *kg/sec*
Validation	2.9	0.0024	0.274	0.054	5213	5.49	2.396
Investigation	7.5	0.0057	0.221	0.13	10294	5.04	5.678

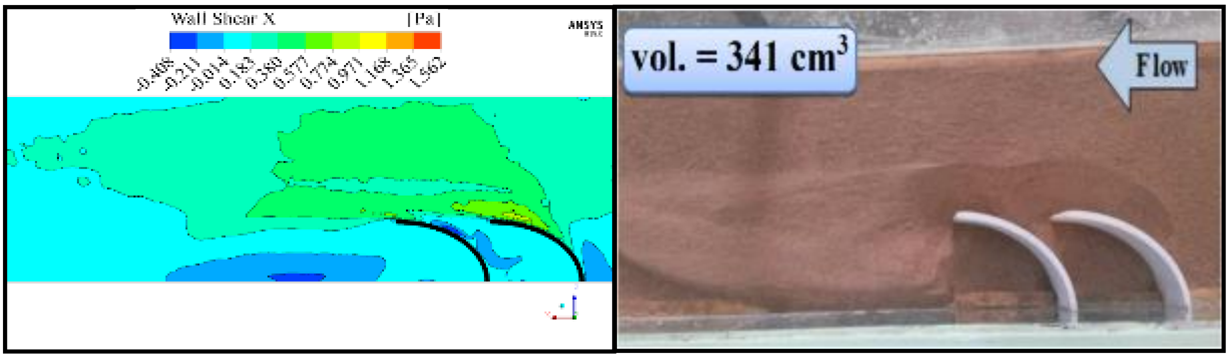
The critical shear stress is the maximum value of stress that the channel bed reaches until the beginning of the sedimentation process, i.e., scour and deposition. To know to scour zone around groynes the critical shear stress must be calculated according to the mean diameter, d_{50}. By relying on **(Julien, 2002)** the average of critical shear stress was found for a fixed bed equal to be 0.37*Pa*.

4. VALIDATION OF THE MODEL

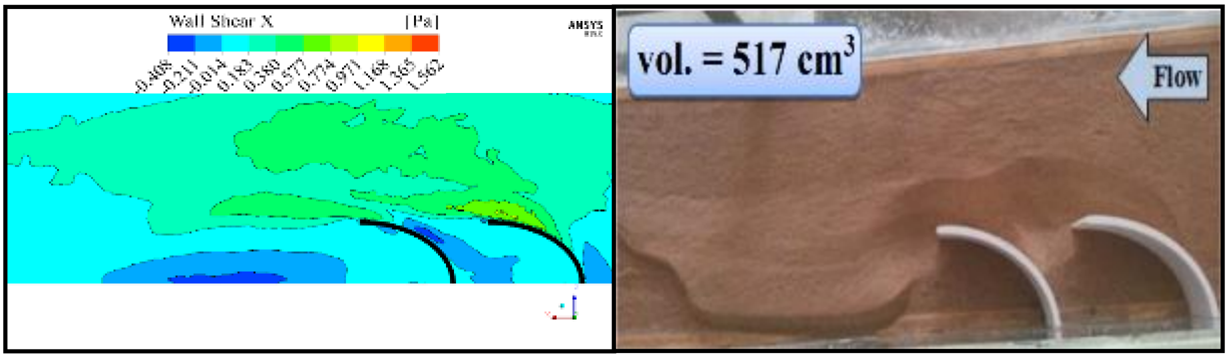
Validation of the model was conducted by comparing the numerical model, CFD, with the results of the laboratory experiments under the same conditions. The CFD model results are presented by contours of the variation of bed shear stress to be compared to the distribution of sedimentation snapshots during laboratory experiments. In these experiments that were conducted with a movable bed, the location and depth of scouring and deposition close to groynes can be observed visually. However, in model runs with a fixed bed, the location of scouring and deposition can be estimated by analyzing visually the contours of bed shear stress about groynes.
Fig.3 shows the obtained contours of the bed shear stress variation by using the model and experiment photo under different conditions and using double elliptic groynes of different spacing between them. Generally, the results showed that shear stress decrease when increasing the spacing between groynes. The maximum bed shear stress formed upstream of the first groyne, i.e., scour zone, while the minimum bed shear stress is located downstream of the first groyne, i.e., deposition zone.
Most of the experiments and simulations under the same conditions gave a good agreement for scouring and deposition locations. The error ratio between experimental and numerical results can be referred to as the fixed bed assumption in the CFD model; unlike in the experimental work, it is a moveable bed. The photos during the experimental results were not taken perpendicular to the groynes, so the image's tendency may give a feeling of mismatch. Moreover, the wood parts used to install the groynes, and the wall may prevent the distribution of sedimentations as is it clear in the experimental photos. Finally, the CFD model has a good ability to a simulation of hydraulic flow around groynes with suitable accuracy.



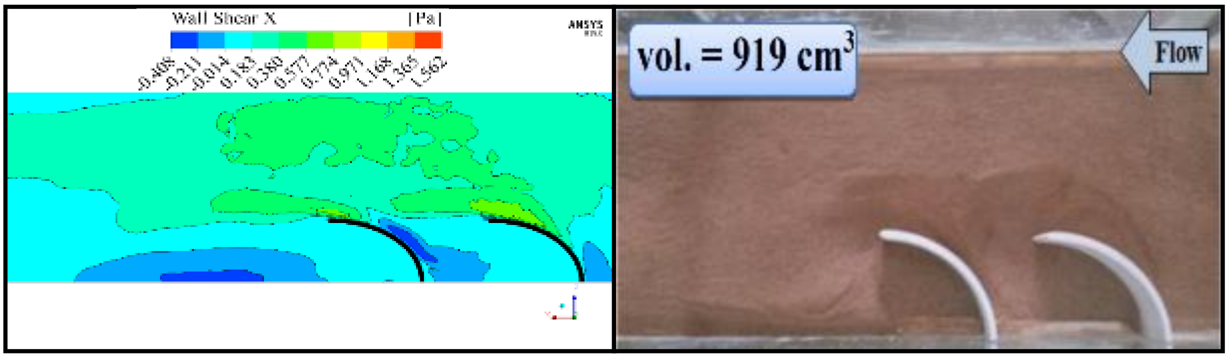
a- Spacing =1Wg.



b- Spacing =1.5Wg.



c- Spacing =2Wg.



d- Spacing =2.5Wg.

Figure 3. Contours of the variation of bed shear stress and experiment photo for double elliptic Groyne, Wg=13*cm*, Lg=20*cm*, y=2.9*cm*, and Q=0.0024m^3/sec.

5. RESULTS and ANALYSIS

This part presents the results and analysis of runs with and without the elliptic groynes under different design parameters. These parameters are the used number of thegroyne, the projection of the elliptic Groyne of Wg=7*cm*, Lg=10*cm*, and the spacing between them of 2Wg with a submergence ratio of the elliptic groynes of 75% was assumed.

5.1 ANALYSIS UNDER CONTROL CASE CONDITIONS

The flume flow simulation was conducted without groynes, as a control case, with a uniform flow rate. The uniform water depth was specified by 7.5*cm* that are corresponding to the discharge of

0.0057m^3/*sec*. The simulation results show the average velocity of flow for 7.5*cm* is 0.195*m/sec*, as shown in **Fig.4**. Moreover, the average bed shear stress of flow is 0.141*Pa*, as shown in **Fig.5**. The ratios change of bed shear stress for three cases of the control case of 162% until the bed shear stress value reaches the critical shear stress at the beginning of the sedimentation process.

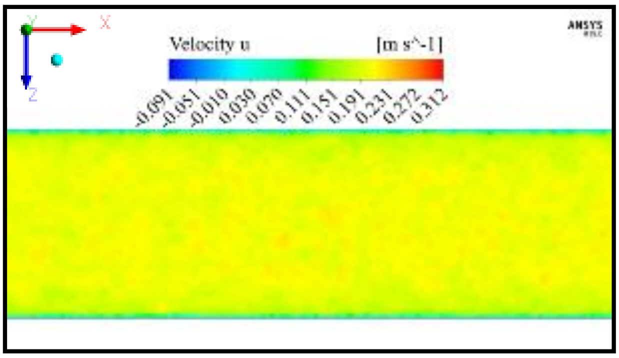


Figure 4. Contours of velocity variation at water surface for control case conditions.

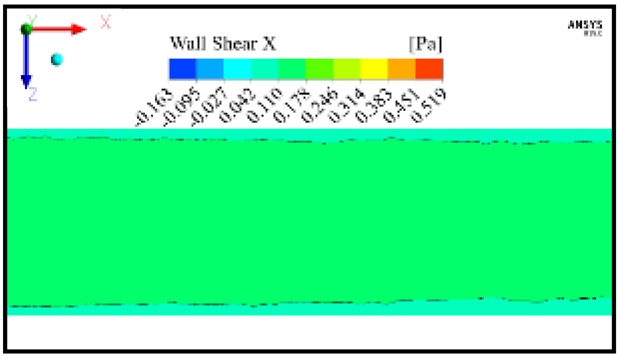


Figure 5. Contours of the variation of the bed shear stress for control case conditions.

Fig.6 shows the locations of the selected cross-sections, which is needed to plot velocity profiles with channel width as well as the location of the first groyne in the channel, flow inlet, and flow outlet. **Fig.7** shows the relationship of velocity profiles with channel width at the height of 5*cm* that equals half of the groyne height for the case of control case to compare with cases of flow with groynes. Moreover, the values of the average velocity of nine cross-sections are 0.213. Finally, the velocity and bed shear stress results are an indicator to compare between a simulation of the open channel flow with and without groynes.

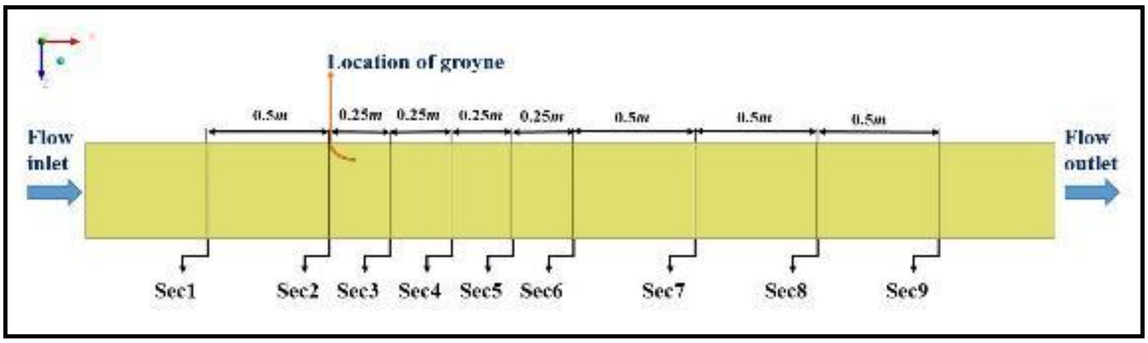


Figure 6. The selected cross-sections locations as well as the first groyne in the channel.

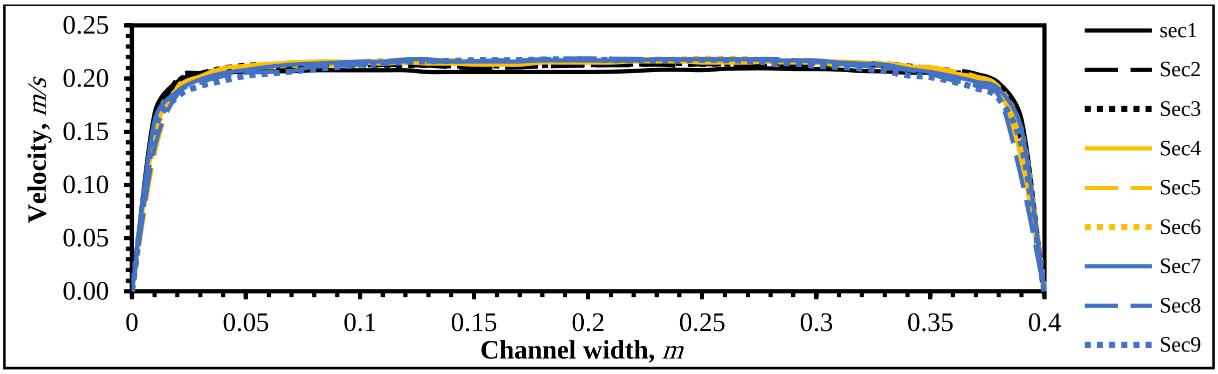
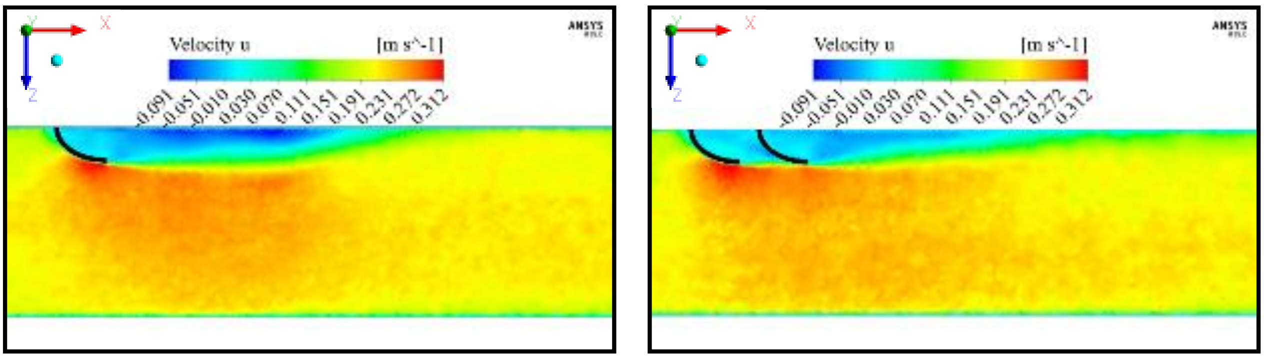


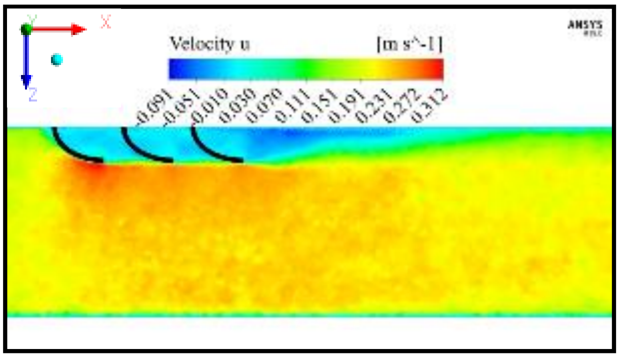
Figure 7. Velocity profiles with channel width for control case conditions.

Fig.8 and **Fig.9** show the contours of velocity variation and variation of the velocity along the streamlines at the water surface around groynes with different groyne numbers for other investigation. The maximum velocity is located near the first groyne as well as the minimum velocity are located after sidewall near groynes. The velocities gradually increased at the front side of groynes, especially near the first groyne. Then, it gradually decreases at the groynes' side and continues after the last groyne to a certain distance. The vortex area decreased with an increase in the groynes numbers as well as the vortex numbers are increased.

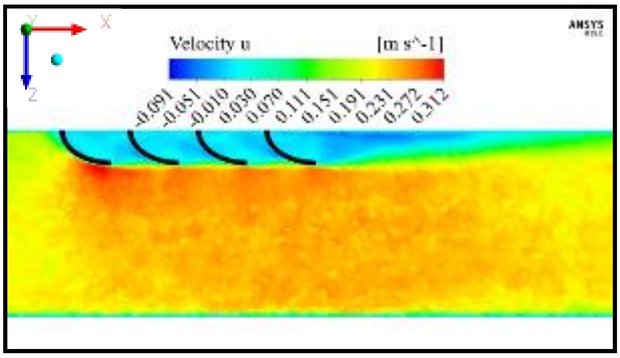
Fig.10 to **Fig.14** presents the relationship of velocity profiles with channel width for other investigation of the elliptic groynes. The relationship between velocity profiles and the channel width at half of the groynes' height is needed to identify the ratio of the velocity increase at the front side of the groynes. The maximum velocity ratio ranges between 24.4-31.5% relative to the values of the control case condition for different groynes numbers. The reference point for measuring the distance of velocity reduction is the first elliptic groyne location, and the first groyne located by a distance of 1*m* from the channel inlet. The velocity profiles in section 1 give the average velocity by a distance of 0.5m from the channel inlet, i.e., before the first groyne's location. Moreover, the velocity profiles show a decrease at the side of groynes under the average velocity for all profiles except the single groyne case. In the non-submerge elliptic groyne, the reduction velocity distance equals 0.5, 0.75, 0.75, 1, and 1*m* from the reference measurement.



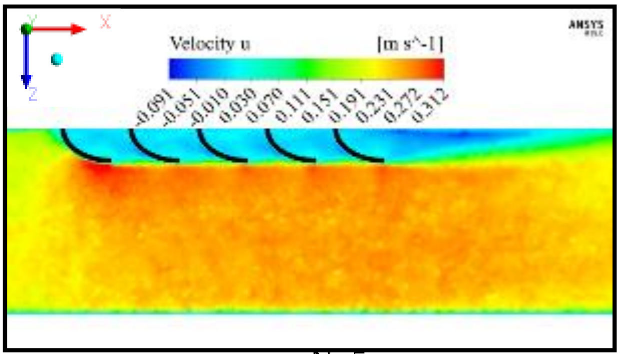
a– N=1 **b**– N=2



c– N=3

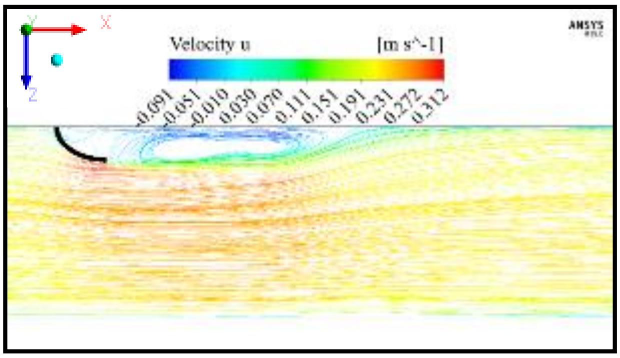


d– N=4

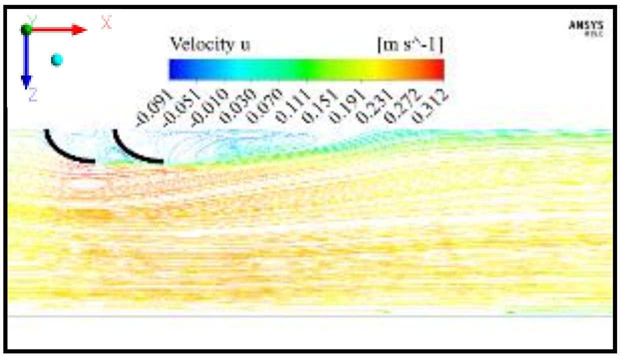


e– N=5

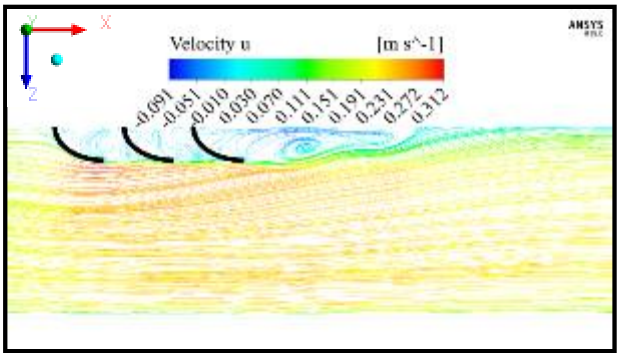
Figure 8. Contours of velocity variation at water surface around groynes with different numbers ofgGroyne, spacing = 2Wg, y=7.5*cm*, and Q=0.0057m^3/sec.



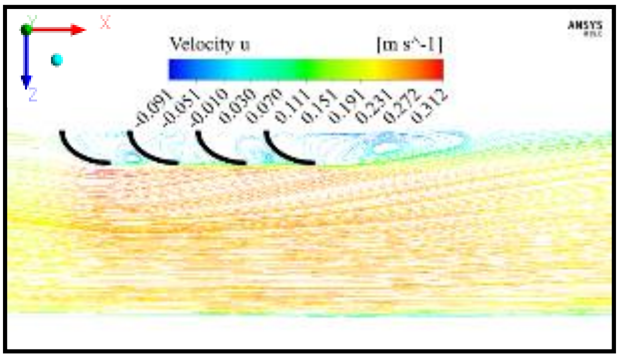
a– N=1



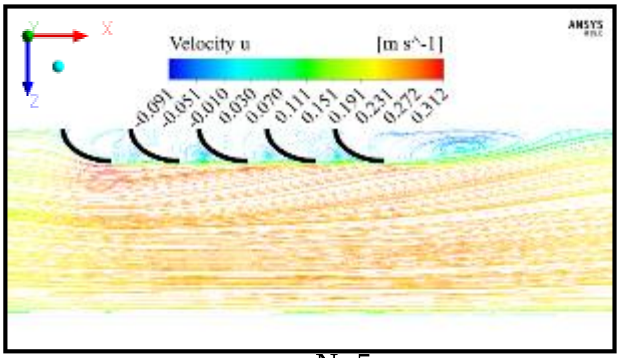
b– N=2



c– N=3



d– N=4



e– N=5

Figure 9. Variation of the velocity along the streamlines at the water surface around groynes with different groyne numbers, spacing = 2Wg, y=7.5*cm*, and Q=0.0057m^3/sec.

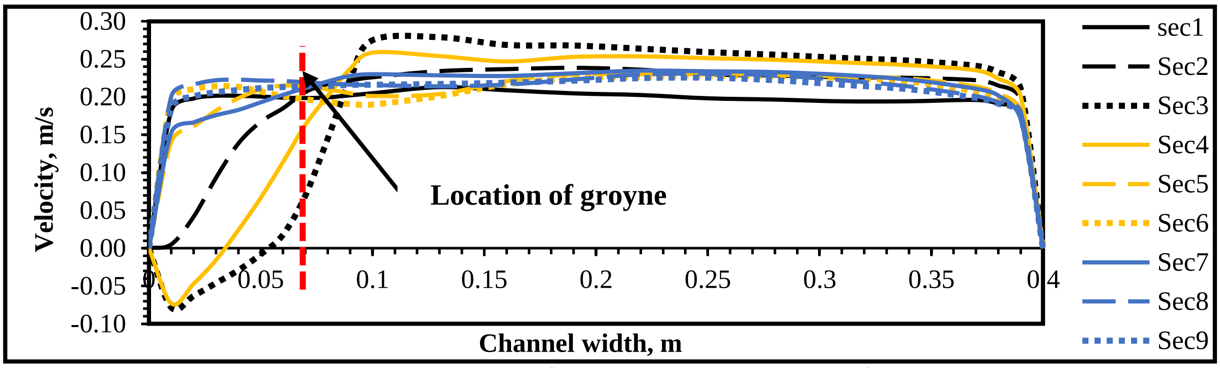


Figure 10. Velocity profiles with channel width for **N = 1**.

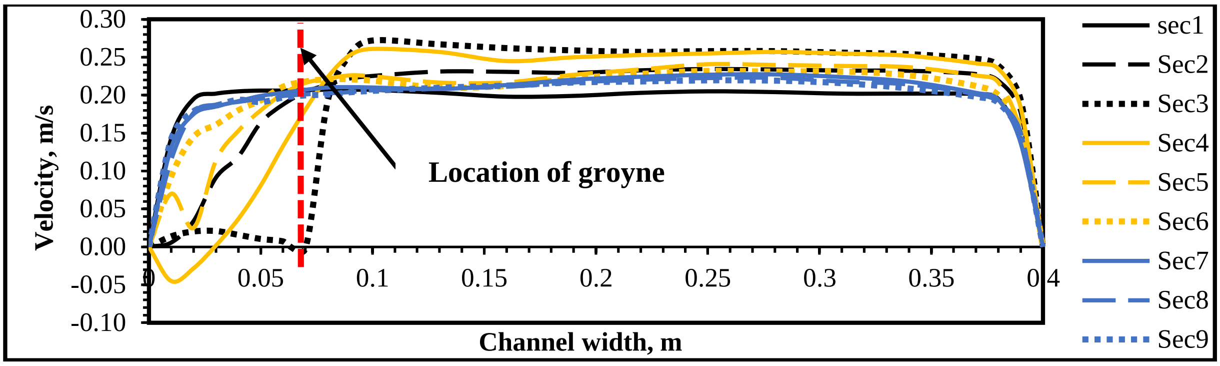


Figure 11. Velocity profiles with channel width for **N = 2**.

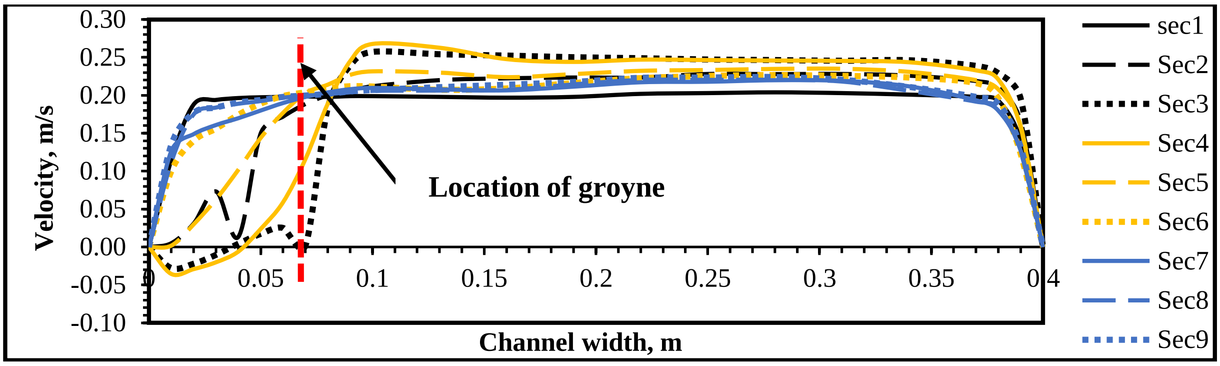


Figure 12. Velocity profiles with channel width for **N = 3**.

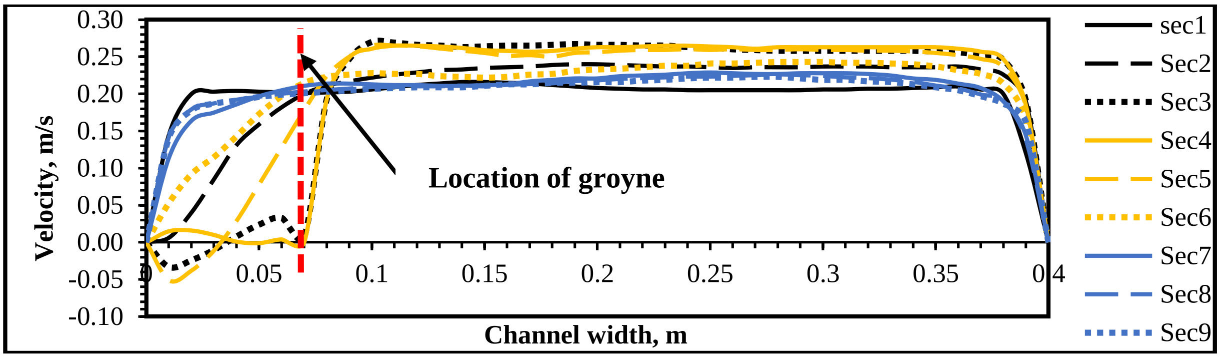


Figure 13. Velocity profiles with channel width for **N = 4**.

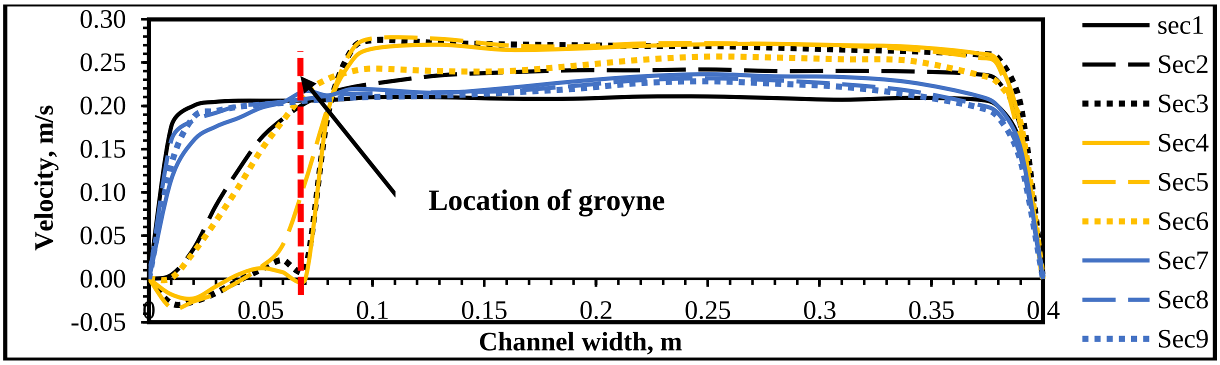
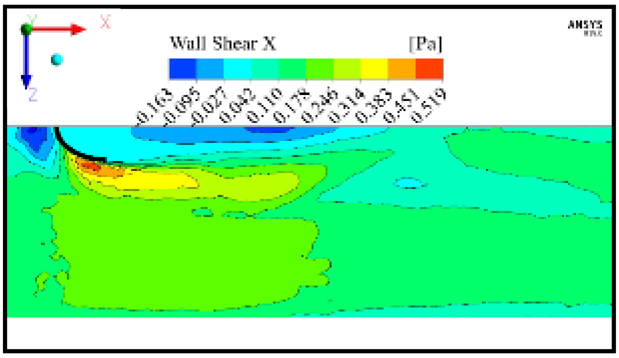


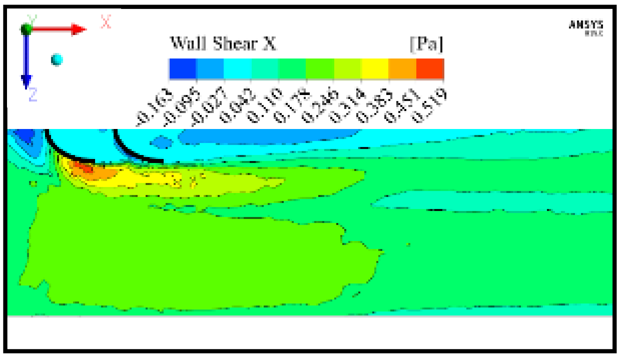
Figure 14. Velocity profiles with channel width for **N = 5**.

Fig.15 and **Fig.16** show contours and the variation of the bed shear stress along streamlines around elliptic groynes for other investigation. The scouring zone is located upstream of the first Groyne.

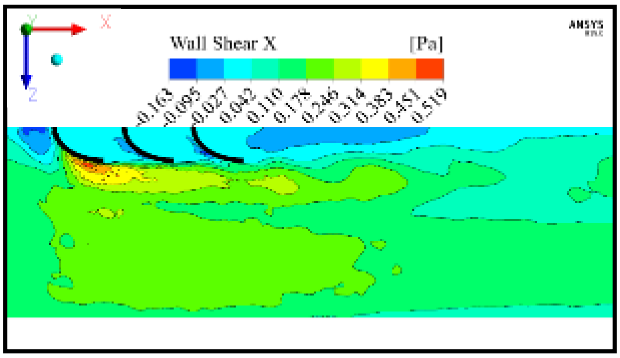
While the deposition is located downstream of the last groyne. The value of minimum bed shear stress is specified by blue color, and a red color specifies the value of maximum bed shear stress. The maximum bed shear stress was formed at the upstream of the first groyne, whatever different the groynes numbers. At the same time, the minimum bed shear stress is located downstream of each Groyne with the sidewall, as well as formed upstream of the first groyne with the sidewall. The variation of bed shear stress along streamlines shows the vortex's base whatever different numbers of groynes. Moreover, the vortex area is formed at the water surface that the largest compared with the vortex at the bed channel.



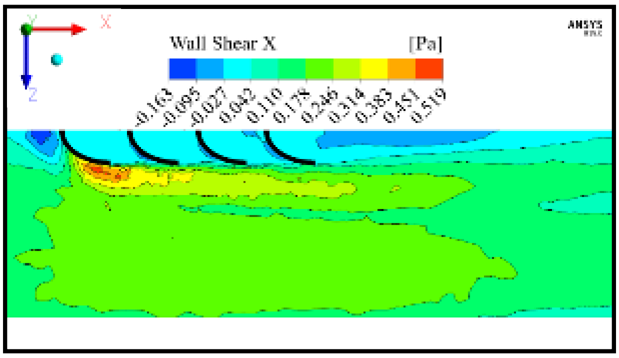
a– N=1



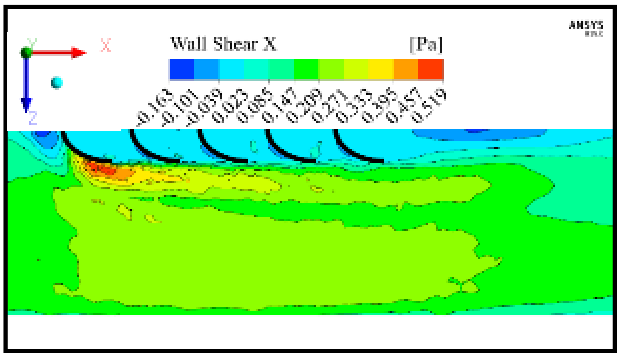
b– N=2



c– N=3

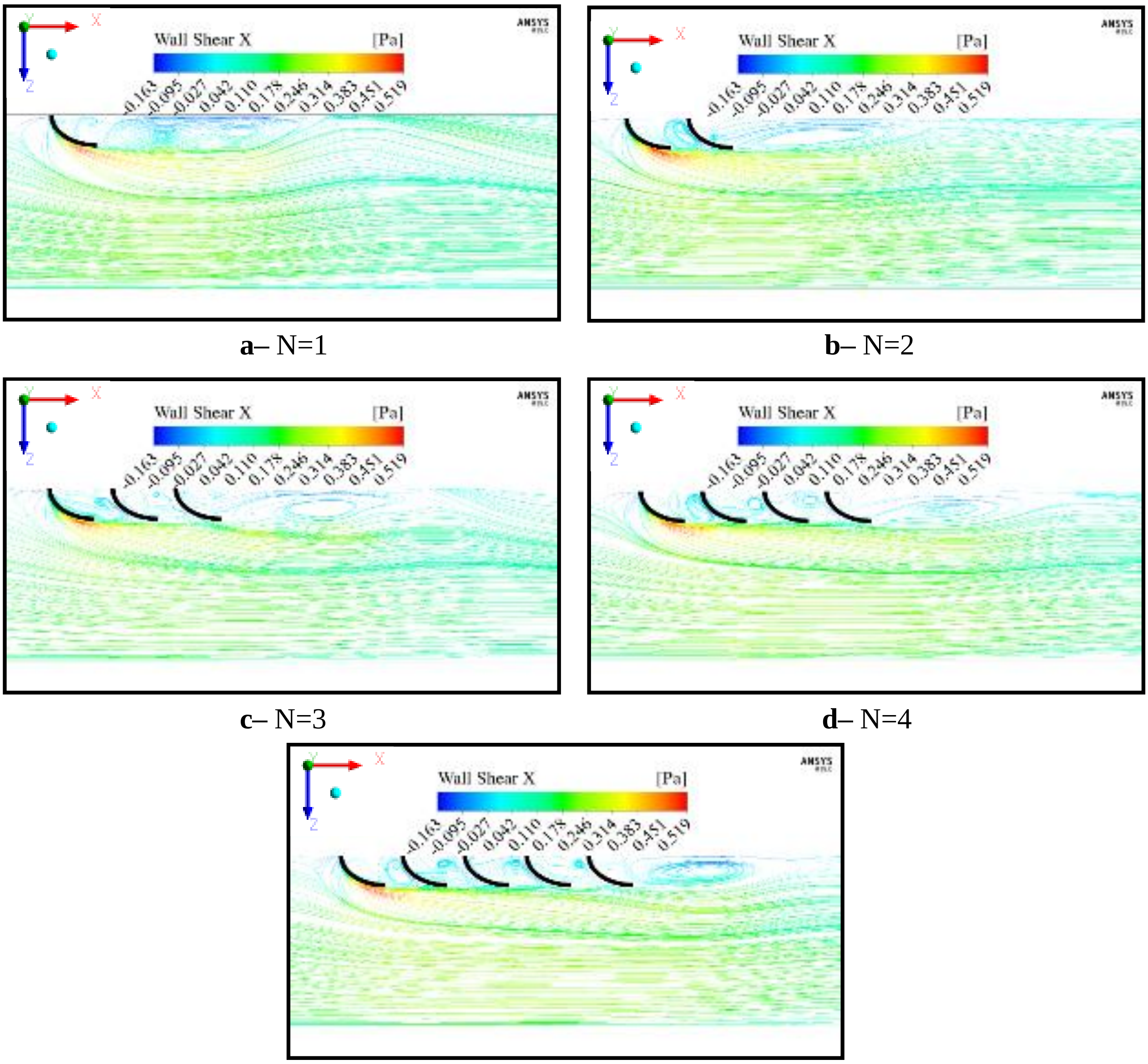


d– N=4



e– N=5

Figure 15. Contours of the variation of the bed shear stress around groynes with different numbers of groyne, spacing=2Wg, y=7.5*cm*, and Q=0.0057m^3/*sec*.



a– N=1 **b**– N=2

c– N=3 **d**– N=4

e– N=5

Figure 16. Variation of the bed shear stress along streamlines at the bed of channel around groynes with different groyne numbers, spacing = 2Wg, y=7.5*cm*, and Q=0.0057m^3/sec.

Table 2. shows the values of minimum and maximum bed shear stress for validation runs and other investigation of the elliptic groynes. The negative sign of the bed shear stress means its direction is opposite to the flow direction .The velocity of the two cases has been calculated for, i.e., two submerged ratios of the groyne, 29% and 75% equal to 0.21 and 0.195*m/sec*, respectively, to open channel flow without groynes, which is needed for determining the variation of velocity to the cases with groynes. Upstream of nearly the first Groyne, the maximum velocity values of water surface increased in cases of different spacing 1Wg, 1.5Wg, 2Wg, and 2.5Wg about 138%, 71%, and 71% and 67%, respectively. In contrast, the range values of maximum velocity increased with the cases of different groynes numbers nearly 52 to 60%. The value of bed shear stress ranges from -0.408 to 1.562*Pa* for the submerged ratio of 29%. At the same time, it ranges from -0.163

to 0.519*Pa* for the submergence ratio of 75%. Critical of bed shear stress has calculated previously equals to 0.37*Pa*, and it's needed to calculate the ratio of increases. The maximum values of bed shear stress increased by 124 to 322% for the submerged ratio of 29%. In contrast, the range values of maximum bed shear stress increased by nearly 28 to 40% for the submerged ratio of 75%.
Although the submergence ratio of elliptic groynes has been increased from 29% to 75%, however, the bed shear stress decreased by about halved, and this is due to the change in flow from non-uniform to a uniform flow as a result of changing the bed slope. Moreover, the groynes numbers don't have much effect on the velocity and shear stress values. Therefore, the groynes numbers depend on the river bank's length to be protected , which may be a straight, a curvature, and a meandering river.

Table 2. The minimum and maximum bed shear stress values for validation runs and other investigation of the elliptic groynes.

N.O.	**Cases**			**Wall Shear**, *Pa*	
				Min.	Max.
1	Validation ,29%	spacing	1 Wg	-0.408	1.562
2			1.5 Wg	-0.300	0.850
3			2 Wg	-0.280	0.830
4			2.5 Wg	-0.340	0.810
5	Other investigation ,75%	Numbers	N=1	-0.163	0.509
6			N=2	-0.133	0.479
7			N=3	-0.082	0.473
8			N=4	-0.127	0.470
9			N=5	-0.115	0.519

5. CONCLUSIONS

1. The maximum bed shear stress was located upstream of the first groyne. However, the minimum bed shear stress was formed at the downstream parallel sidewall and formed at upstream of the first groyne with sidewall.
2. The velocities increase gradually at the front side of groynes , especially near the first groyne. It then decreases gradually at the groynes' side and continues after the last groyne to distance.
3. The maximum bed shear stress range about 124 - 322% for the submergence ratio of 29%. At the same time, it ranges from about 28 - 40% for the submergence ratio of 75%.
4. With double elliptic groynes, the bed shear stress is decreased with an increase in the spacing between groynes, as well as and the best spacing between the double elliptic groynes is 2Wg.
5. The groynes numbers don't have much effect on the velocity and shear stress values. Therefore, the groynes numbers depend on the river bank's length to be protected, which may be a straight, a curvature, and a meandering river.

NOMENCLATURE

Q = Flow discharge, m^3/sec and kg/sec.
D_H = Hydraulic diameter, *m*.
Lg = Groyne length, *cm*.
Wg = Groyne width, *cm*.
N = number of groynes.
b = spacing between groynes, *cm*.
d_{50} = Mean diameter of soil, *mm*.
T.I = Turbulence Intensity, *%*.
Fr = Froude number.
Re = Reynolds number.
CFD = Computational Fluid Dynamics.
SST = Shear Stress Transport
FVM = Finite Volume Method.
VOF = Volume of Fluid.
PISO = Pressure-Implicit with Splitting of Operators.

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