Numerical Investigation of the Combined Slot Effect on the Erosion Pattern Around a Combination of Spur Dikes in Series

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Research Article

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Numerical investigation of the combined slot effect on the erosion pattern around a combination of spur dikes in series

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Abstract

Modifying the river course for flood control, prevention of bed erosion, bank protection, and the regulation of river width are among the goals of spur dikes incorporation. The common spur dikes have simple (I), L and T geometrical shapes. The present research has been conducted to reduce the scour depth in front of the spur dikes and improve the sedimentation conditions for the LTT combination of spur dikes in series by investigating different combinations of slots in the body of the spur dike; using numerical methods. The slot dimension was taken equal to 10% of the effective area of the spur dike body. Finally, the (L5, S-W, W-Wi, T5, S-W) combination contained the slots in the web and wing of the first and third spur dike also the slot at the web of the middle spur dike was found as the best combination of slots. This combination conducted to reduce the scour depth about 6.8% and increase the deposition about 52% comparing by the spur dikes without slots. Reducing the scour depth and increasing the sedimentation rate of materials between the spur dikes. Also, the maximum scour depth decreases up to 20%. The results revealed that the presence of slots in spur dike structures and their different positions have complicated and considerable influences on the form and morphology of the erodible bed which could be the topic for further researches.

Keywords: T-shaped spur dike, L-shaped spur dike, Mobile bed, Bed erosion, Numerical simulation, simple spur dike.

1. Introduction

Rivers bank erosion and bed changes have always been of interesting for engineers. Various methods and structures such as spur dikes to control bank erosion and bed river changes. Spur dikes could be implemented with simple, L –shaped, T-shaped, triangular and other forms have different angles with respect to the flow direction. They decrease the flow velocity between each other which conducts the reduction in flow intensity and increases the sedimentation. Control of scouring around hydraulic structures is one of the important stability issues in design to prevent the damage of structures. Scouring around spur dikes is produced by down-flow and initial vortices at the upstream corner of the spur dike and also secondary vortices and wake at the middle and its downstream corner (Barbhiuya & Dey, 2004; Coleman et al., 2003). Therefore, different methods are proposed to reduce scouring and prevent undesirable effects against the stability of the structure. One of these controlling methods is the change in the flow pattern and reduce its strength. Using collars, vanes, a combination of spur dikes in series, and slots are among the main solutions for changing the flow pattern (Chiew, 1992; Nayyer et al., 2019). Slots reduce the strength of down-flow and horseshoe notices by diverting the down-flow at the upstream face of the spur dike and the side flows around it. Slots induce horizontal flow jet in the vicinity of the bed which conducts the reduction in pressure gradients and down-flow transfer away from the structure. All these effects lead to a reduction in scouring around spur dikes (Kumar, 1996). Chen and Ikeda (1997) performed many studies regarding the flow

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pattern around a single spur dike in the straight reach, experimentally. They studied the formation, development, and transfer of horizontal eddies around the spur dike nose and concluded that the shedding eddies are separated from the tip of the spur dike and periodically transferred downstream. Scour depth reduction around bridge pier; using the slots under different conditions is investigated by various researchers such as Kumar et al. (1999), Babar et al. (2000), Heydarpour et al. (2007), Moncada-M et al. (2009), Heidarnejad et al. (2010), Tafarojnoruz et al. (2012). In all of these researches, the efficiency of slots is approved, but fewer researches have been done on the erosion around the spur dikes which are reviewed here. Ho et al. (2007), using Yeo et al. (2005) results done on the flow pattern around a spur dike to validate the flow-3D numerical model. Finally, they found the best position of the spur dike in a rectangular canal. Zhang and Nakagawa (2008), performed some experiments for permeable and impermeable single spur dikes on the erodible beds. They showed that the maximum scour depth around the permeable spur dike is 50% lower than the impermeable spur dike. In the research which performed by Keshavarz et al. (2009) through numerical modeling of the flow around the spur dike which was positioned both perpendicular and oblique to the bank, they demonstrated that the K-ε turbulence model provides the best estimation of scour depth in comparison with the experimental results. Acharya and Duan (2011) conducted a 3D numerical study of the turbulent flow pattern around a series of sharp-edged spur dikes along a straight channel with constant and mobile beds using FLOW-3D software. They used the K-ε turbulence model for simulation of the flow and compared the results of the simulation with the experimental ones. Hasanpour et al. (2012) investigated the slot effect on the temporal development of scouring around the spur dike. Their research revealed that the slots reduce the scour depth around spur dikes. Maximum scour depth is reached for the slot height equals to the flow depth. Scour depth reduction has been reported by about 28%.

Influence of flow rate on the flow pattern around a simple spur dike was investigated by Vaghefi et al. (2016). They used the VOF model to detect the water surface and K-ε model for turbulence for turbulence model. They found that the numerical model could simulate the flow pattern around a spur dike. 3D simulation of flow around different spur dikes was performed by Kumar and Malik (2016) using the Ansys Fluent software. They investigated various types of spur dikes and stated that the effect of Froude number on the protection length or rotational region is negligible. Also, they found that the shape of spur dike was more efficient on the bed layer than the other layers. Lee and Jang (2016) investigated the effect of distance between two adjacent spur dikes in a series on the bed scouring and flow pattern. They stated that the scour depth was increased by increasing the distance between the spur dikes. Gu et al. (2016) studied flow around spur dike in series for finding appropriate CFD models. The comparisons between the CFD yields and experimental data appear that all turbulence models (K-ε, RNG and LES) are able to simulate the three-dimensional flow around spur dike in series with proper conformity.

Monjezi et al. (2017) studied the heights, widths and distance effects of the slot in the spur dike body on rip-rap stability at the bend for flow rate equals to 27 l/s. They proposed a dimensionless parameter named slot ratio (x/l) which described the ratio of the distance between the slot edge and the spur dike tips (x) and spur dike length (l). They showed that for the slot ratio equals to 0.25 was more stable than for the slot ratio equals 0.75.

Dorosti et al. (2018) studied the effect of distance between the slot and spur dike tip on erosion and sedimentation pattern. They showed that the presence of the slot in the body of spur dike near the bed conducted better performances in providing the balance between sedimentation
height and local scouring in comparison with the conditions in which the slot situated near water surface or a spur dike without slot. The former improved the performance of spur dike up to 60%. Masjedi and Jafari (2018) used a slot in the body of the spur dike to control scouring around the spur dike located within a 180-degree bend. The experiments were performed for a single spur dike without slot (control state) and the spur dike with slot situated in four positions and two heights for four flow rates. They showed that the amounts of reduction in scouring related to the location and height of the slot and minimum scour depth occurred for the slot in the vicinity of the spur dike tip. Also, the scouring is increased by increasing the distance between the slot and the spur dike tip. Nayyer et al. (2018) investigated the scouring around a simple (I shape) spur dike under the influences of the other shapes of spur dikes in its neighborhood. They showed that the best combination for minimizing the scour depth around a series of spur dikes is I shape, T shape, and L shape, respectively (ITL) from upstream to downstream. Kumar et al. (2018) investigated scouring around the simple and T-shaped spur dikes. Regarding the results, they concluded that the T-shaped spur dikes were more effective in the protection of the bed and also the reduction in the scour depth and damage to the hydraulic structures. Therefore, where the protection of hydraulic structures is essential, using a T-shaped spur dike is recommended and the simple spur dike should be implemented where diversion and displacement of the flow are of high importance.

Vaghefi et al. (2018) studied flow conditions around the T-shaped spur dike in the presence of a protective structure situated oblique or perpendicular to flow, by the numerical model. This study revealed that the maximum shear stress in the vicinity of bed for the protective structure in the attracting and repelling states increased by 23.5% and 17.6%, respectively, in comparison with the vertical state. This study showed for the angles less than 15 degrees in the oblique protective structure, the strength of secondary flow increased in the vicinity of the main spur dike is 24% for attractive spur dike and 15% for repellent spur dike in comparison with the perpendicular one. By increasing the degrees to 20 and 30 degrees, the strength of secondary flow decreased about 14.6% and 15.5%, respectively for attractive and repellent spur dike in comparison with the perpendicular one.

The morphological effects around a triangular spur dike positioned a slot in its web in a 90-degree bend was the topic of the research done by Meymani et al. (2019). They investigated bed changes for a rectangular slot with an opening equals to 10% of the effective area of the spur dike in plane for angles and hydraulic conditions in the problem. Their studies revealed that in the presence of the slot augmented the distance between the scour pits at the outer bank and reduced the maximum scour depth. Farzin et al. (2019) have used GMDH and GEP models for analyzing different parameters of protective spur dike for reduction of bed scour depth. They reported that the ratio of protective spur dike's length to the main spur dike length is the most impressive parameters for decrease of scour depth. Scouring around a spur dike with the mixture of gravel and sand performed by Pandey et al. (2019) revealed that it was mainly affected by the sediment mixture properties. Thus by reducing the heterogeneity of the sediment mixture, the scouring rate increased. Yang et al. (2019) investigated the maximum water depth upstream of the permeable spur dike within a bend. They stated that the change in the depth is a function of the pattern used for spur dikes installation within the river bend. They showed that the maximum depth occurs where the spur dikes are installed at the half of the bend with 75-degree angle. Furthermore, the maximum water depth occurs at the section where the spur dike encounters the outer bank of the bend.
Nayyer et al. (2019) investigated the flow parameters around the spur dikes in a combination with different usual shapes (I LT) situated in series, experimentally and numerically. They stated that the (LTT) combination had the highest effect on reducing the velocity, shear stress and turbulence intensity around the spur dikes. So, it seems that a combination of different geometries could have a considerable effect on reducing the scouring and increasing the sedimentation between spur dikes. Temporal scour depth around spur dike were investigated by Pandey et al. (2020). They used vertical wall spur dike and measured scour depth according to time variation. They concluded that with increasing the threshold velocity ratio, the Froude number and the flow depth-particle size ratio, scour depth increased. Zamani et al. (2021) have compared the Flow-3D and experimental output of the effect of spur dikes position on the hydraulic characteristic and scouring conditions of lateral intakes. They reported that the location of the spur dike in front of the intake has achieved the best scour and bifurcation ratio. As reviewed here, widespread studies have done on the performances of spur dikes in different conditions, which indicate the importance of this structure in the river engineering including the control of river bed and banks protection from erosion and also control of flow conditions in the river. So, the stability control of the structure from scouring is of great importance. Different methods such as the use of protective spur dikes, collars, rip-rap, changes in the geometry of spur dikes and creating slots in the body of spur dikes are among the methods used for this purpose. Use of the combination of spur dikes in series with different geometries is the approach which has reduced scouring around the spur dikes. The utilize of numerical models to anticipate and evaluate erosion around hydraulic structures is essential in various water resource management issues, such as scouring and erosion control, hydraulic characteristic and streamline analyzing and sedimentation. Therefore, in this research, after verification tests of the numerical model, a combination of slots in the body of the combined series of spur dikes are done, and the changes in the scour depth around them are investigated, using a numerical model.

2. Numerical model and the governing equations
Conservation of mass and momentum in differential forms are the governing equations for fluid and solid phases. These. Equations are solved by numerical methods. Soft-ware such as Flow-3D developed to model different phenomena. This software profits some special techniques which permit to model various physical and numerical conditions for real or experimental models. The general forms of mass and momentum conservation equations in Flow-3D software are given by expressions (1) and (2), respectively:

\[ V_F \rho \frac{\partial}{\partial t} + \frac{\partial}{\partial x} \left( \rho uA_x \right) + \frac{\partial}{\partial y} \left( \rho vA_y \right) + \frac{\partial}{\partial z} \left( \rho wA_z \right) = 0 \]  

\[ \frac{1}{V_F} \left\{ \frac{\partial}{\partial t} \left( uA_x \right) + vA_y + wA_z \right\} = (-1/r) \left( \frac{\partial}{\partial x} \left( \frac{\partial}{\partial x} \right) + G_x + f_x - b_x \right) \]  

\[ \frac{1}{V_F} \left\{ \frac{\partial}{\partial t} \left( vA_y \right) + uA_x + wA_z \right\} = (-1/r) \left( \frac{\partial}{\partial y} \left( \frac{\partial}{\partial y} \right) + G_y + f_y - b_y \right) \]  

\[ \frac{1}{V_F} \left\{ \frac{\partial}{\partial t} \left( wA_z \right) + uA_x + vA_y \right\} = (-1/r) \left( \frac{\partial}{\partial z} \left( \frac{\partial}{\partial z} \right) + G_z + f_z - b_z \right) \]

where \( u, v, w \) are velocity components and \( A_x, A_y, A_z \) are the fractional area opened to flow respectively, in \( x, y, z \) directions, \( V_F \) is the fractional volume opened to flow, \( p \) is fluid density, \( G \) is body acceleration, \( f \) is a term of viscous acceleration and \( b \) is flow losses in across porous baffle plate or porous media (Flow Science, Inc., 2008).
In Flow-3D software, FAVOR (Fractional Area Volume Obstacle Representation) and VOF (Volume of Fluid) methods are used in simulating. FAVOR method is used for modeling of the solid surfaces, geometries, and volumes. VOF method is used to trace the water surface in a water-air two-phase flow. Expression (3) is proposed for defining the free surface profile.

\[ \nabla \cdot (\rho \frac{\mathbf{u}}{\rho} F) + \nabla \cdot (\mathbf{u} F) = 0, \tag{3} \]

where \( F \) function is the index of volume percentage of the water phase in a cell; it ranges between zero (for the case in which the cell is full of air) and one (for the case in which the cell is full of water) (Hirt & Nichols, 1981).

Sediment transport is formed by two mechanisms; bed load and suspended load. For modeling the bed load different methods such as Meyer Peter and Müller, Von Rijn are proposed. The suspended load is modeled, using ADE (Advection-diffusion equation) given by expression (4):

\[ \frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = \mathbf{V} \cdot (\nabla c) + \mathbf{W} \cdot (\nabla c) - x \left( \frac{\partial c}{\partial x} \right) - z \left( \frac{\partial c}{\partial z} \right) \tag{4} \]

In this equation, \( c \) is the concentration of sediment, \( \mathbf{U} \) average Reynolds velocity of flow, \( \mathbf{W} \) denotes fall velocity of sediment particles, \( x \), and \( z \) represent the dimension along the main direction and vertical direction, respectively. Also \( \Gamma \) is the coefficient of dispersion defined as the ratio of turbulent viscosity to Schmidt number (Flow Science, Inc., 2008).

2.1. Turbulent models

Studying the characteristics of turbulent flow is very complex and time-consuming, as in this type of flow; currents with different momentums encounter each other and reduce the fluid kinetic energy. This dissipated energy is converted to heat in a one-way process. All the above-mentioned issues should be taken to account when investigating the turbulent flow. Therefore, numerical models are capable of presenting valuable information to solve turbulent problems.

2.1.1. K-\( \varepsilon \) Turbulence model

K-\( \varepsilon \) Model is a two equations model that means it includes two equations to represent the turbulent properties of the flow. \( K \) is the variable that represents the turbulent kinetic energy and \( \varepsilon \) (m²/s³) is the variable that represents the turbulent dissipation. The transport equation, \( \varepsilon_T \) for turbulent dissipation, is defined as expression (5):

\[ \frac{\partial \varepsilon_T}{\partial t} + \mathbf{u} \cdot \nabla \varepsilon_T = \nabla \cdot \left( \frac{\nu T}{\varepsilon_T} \nabla \varepsilon_T \right) + \frac{\mathbf{V} \cdot \nabla \varepsilon_T}{\varepsilon_T} + \frac{\mathbf{W} \cdot \nabla \varepsilon_T}{\varepsilon_T} - x \left( \frac{\partial \varepsilon_T}{\partial x} \right) - z \left( \frac{\partial \varepsilon_T}{\partial z} \right) = \frac{C_{DIS_0} \varepsilon_T}{K_T} \left( P_T + C_{DIS_2} \varepsilon_T \right) + \text{Diff} \cdot C_{DIS_2} \left( \varepsilon_T^2 / K_T \right) \tag{5} \]

In expression (5), CDIS\(_1\), CDIS\(_2\) and CDIS\(_3\) are dimensionless parameters with default values of 1.44, 1.92 and 02, respectively, for K-\( \varepsilon \) model (Flow Science, Inc., 2008).

2.1.2. RNG turbulence model

RNG turbulence model is capable of explicitly expressing the coefficients in K-\( \varepsilon \) model which are derived experimentally. This model could produce more accurate results in strong shear flow regions but small turbulence intensity. RNG turbulence model implements statistical methods to derive averaged equations for quantities like turbulent kinetic energy. The values of parameters CDIS\(_1\) and CDIS\(_2\) in this model are 1.42 and 1.68, respectively.

2.1.3. LES turbulence model

This turbulence model is time dependent and three-dimensional. Also an initial value should be given to the fluctuations or at the inflow boundaries. Applying these is costly but this model presents more accurate results with respect to RNG turbulence model (Hirt & Nichols, 1981).
2.2. Evaluation and comparison criteria
The evaluation and comparison of numerical and experimental values were made using three criteria, mean absolute error (MAE) and root mean square error (RMSE) and coefficient of determination ($R^2$) and defined by Equation (6): where $O$, $P$ and $n$ are the experimental values, values obtained in the numerical model and total number of data.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} O_i^2 - \left(\frac{\sum_{i=1}^{n} P_i^2}{n}\right)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}}$$

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |O_i - P_i|$$  \hspace{1cm} (6)

3. Materials and methods
3.1. Experimental model
In order to determine the convenient turbulence model and the mesh sizes for a particular phenomenon, verification tests are usually proposed. For this purpose, the results obtained by the numerical model are compared with those measured in laboratory tests or field data. The experimental set up in this study is a rectangular canal with 14m length, 1.5 m width and walls made of Plexy-glass for performing the experiment on the combination of spur dikes in series with L-shaped, T-shaped, and I-shaped geometries. The canal bed is covered with a layer of homogeneous sediment with a mean diameter of 1mm ($D_{50}=1mm$) and geometric standard deviation of 1.21 ($\sigma_g=1.41$) and height of 30cm done by Nayyer et al. (2019). In their experiment the flow rate ($Q$) and flow depth ($y$) corresponding to the threshold of sediment motion ($U/U_{cr}=0.95$) were 28.5 l/s and 6cm, respectively. Also, the geometric characteristics of the used spur dikes in the research by Nayyer et al. (2019) are shown in Fig.1 in which $a=3L$, $L=L_t$, and $L/B=0.23$. Experimental conditions and results of scouring around different combinations are given in Table 1. In this table $d_{s1}$, $d_{s2}$, $d_{s3}$, and $d_{ave}$ are the scour depth in the first, second, and third spur dikes and their average, respectively. As shown in this table, the LTT combination of spur dikes in series exhibits the minimum scour depth in the first, second, and third spur dikes. Therefore, this combination of spur dikes is used for simulation and investigation of creating slots in the web and wing of the spur dikes in the numerical model.

3.2. Numerical model
As stated before, Flow-3D software was incorporated for simulation of the experimental model. In Fig.2 a view of the geometry and boundary conditions used in the modeling are shown. The boundary condition in the model includes wall, symmetry and pressure which were used for the bottom ($Z_{min}$) and canal walls ($Y_{max}$ and $Y_{min}$), free surface ($Z_{max}$), inflow boundary ($X_{min}$), and output boundary($X_{max}$), respectively. The sediment bed is defined at the bottom of the canal according to the experimental canal with the mean sediment diameter equal to 1mm. Modeling was performed in the software using two flow rates values of 28.5 and 25.65 l/s with 6 cm depth and velocities of 0.32 and 0.29 m/s.

For investigating the numerical model and obtaining the appropriate result RNG, K-Ɛ, and LES turbulence models were used. statistical comparison of scour depth for the experimental and numerical results for LTT combination are shown in Table 2. According to the FAVOR method, and in order to increases the simulation accuracy of the numerical model, in the vicinity of sensitive geometries, as shown in Fig. 2 (B), several mesh planes were used. The total number of mesh cells in the longitudinal, lateral and vertical directions is equal to 222, 84 and 30, respectively, so the cell size is variable for each direction. Also, the maximum aspect
ratio in all directions is equal to 3. Therefore, for the continuation of simulation and considering the dimensions of the intended meshing, use was made of the K-ε turbulence model. A comparison of bed change between the eroded bed in the experimental model by Nayyer et al. (2019) and the numerical model in this research is shown in Fig. 3.

3.3. Slots dimensions and shapes
As stated before, the goal of this research is the investigation of the effect of the slot on the scour depth of spur dikes in series. Therefore, the LTT series of spur dikes was introduced as the optimum combination obtained by Nayyer et al. (2019) and a slot introduced in the first the designed slots also were considered for this combination. The slot shape was considered as a horizontal rectangle in the body of spur dikes with the ratio of \( a_s/b_s=4 \) (\( a_s \) is the length, \( b_s \) is the width and \( t \) is the thickness of the slot) and the opening area of 10% of the structure effective area (Chiew, 1992). Also, the position of the horizontal slots was taken close to the bed level (Dorosti et al., 2018). Fig. 4 shows the defined geometry and position of the slot in the spur dike body. In cases where the slot is defined in both the web and wing of the spur dike, the opening area is 10% of the structure effective area, too.

The intended combinations in the present research were designed considering the slots in the web and wing of the spur dikes, which are given in Table 3. In this table, the position of the slot (s), in the web (W) and wing (W_i) are written at the side of each spur dike and its situation. The change in the position of the pits also was determined according to the obtained results.

4. Results and Discussion
4.1. A Comparison Between Numerical and Experimental Results
According to the results of section 3.2, all the models in table 1 were simulated for the purpose of comparison. The results of maximum scour depth for the first, second and third spur dikes in comparison to the experimental results are shown in Fig. 5. As seen, this numerical model has presented acceptable results with good accuracy. The statistical indices values for these models are equal to \( R^2=0.97 \), RMSE=0.28 and MAE=0.24. The LTT combination of spur dikes in series was modeled during 700 seconds and it was observed that after 500 seconds of simulation, the scour depth reached the equilibrium condition as shown in Fig. 6. As is observed at about 30% of simulation duration the scour depth reached 85% of the equilibrium scour depth.

4.2. Slot Effect On Erosion
Due to the complexity associated with investigating the effect of the slot on the bed and also changes in the scour depth around the spur dikes, this effect should be investigated with respect to different aspects. Therefore, the maximum scour depth, sedimentation, and overall erosion of the bed are among the parameters which are analyzed in this research. The first spur dike in all the combinations of Table 1 had the highest scour depth. Therefore, in order to investigate the effect of the slot in the first spur dike, models No. 1 to 8 were simulated to be examined for two different flow rates. Models No. 1 and 5 were without slot, models No. 2 and 6 had a slot in the web of the first spur dike, models No. 3 and 7 had a slot in the wing of the first spur dike and models No. 4 and 8 had slots in the web and wing of the first spur dike. The results showed that the scour depth in the first spur dike is reduced in any slot position. The minimum reduction corresponds to models No. 3 and 7 with the slot in the wing which is about 5% with respect to the state without slot. The maximum reduction
corresponds to models No. 2 and 6 with a slot on the web which is about 55% with respect to the state without slot. Models No. 4 and 8 also had about 25% reduction in the scour depth at the position of the first spur dike. The noteworthy point in all these models is that although the scour depth is reduced at the position of the first spur dike, it has increased at the positions of the second and third spur dikes. Therefore, changes in the erosion and sedimentation should be investigated over the entire bed length so that the effect of slot in the first spur dike is determined along the entire bed length. Fig. 7 shows changes in the scour depth and in the ratio of the sedimentation to erosion in models No. 1 to 8. As is seen, in models No. 2 and 6 the mean scour depth of the spur dikes is reduced but the ratio of sedimentation to erosion is reduced, too. The other point is related to models No. 2 and 6 where the maximum scour depth has occurred at the position of the second spur dike which is different with respect to other models. Models No. 3 and 7 also exhibit an increase in the mean scour depth at the position of spur dikes which is due to an increase of the scour depth at the positions of the second and third spur dikes in the combination of the spur dikes. In these models also the ratio of bed sedimentation to erosion is reduced. Ultimately in models No. 4 and 8 it is seen that the mean scour depth has a significant reduction and on the other hand the ratio of sedimentation to erosion had a considerable increase. In fact, models No. 4 and 8 which have slots in the web and wing of the first spur dike exhibit acceptable performance in terms of both reductions in the mean scour depth and sedimentation. Fig. 8 shows the bed level for both of these models.

As stated before, the presence of the slot in the first spur dike, in any case, causes a reduction of scour depth in the first spur dike and increase of scouring in the second and third spur dikes. Therefore, in models No. 9 to 14, the slot in the web and wing of the first spur dike is constant and the slot in the spur dikes at the second and third positions is investigated. Considering that scouring increases at the second and third spur dikes, that model would yield the best result. It shows a minimum increase in the scour depth at the spur dikes of the second and third positions, the maximum rate of sedimentation, and minimum rate of erosion over the entire bed length. Table 4 depicts a summary of the obtained results from simulations of models No. 9 to 14. As is observed, changes in the bed in all the models are associated with increased sedimentation and reduced erosion of the entire bed length. The maximum sedimentation corresponds to model No. 11 and the minimum one corresponds to model No. 15. In model No. 11, the slot is created in the web and wing of the first and third spur dikes and concerning the middle (second) spur dike it is created on the web. Also in model No. 15, the slot is created in the web and wing of the first spur dike and in the web of the second and third spur dikes. Change in the bed erosion over its entire length is not significant in all the models and there is not much difference between them, but considering the ratio of sedimentation to erosion it is seen that the best ratio belongs to model No. 11. In fact, the height of sedimentation in model No. 11 has a higher value with respect to the scour depth which indicates good sedimentation in this model alongside similar erosion in other models. Considering the maximum scour depth also it is seen that all the models No. 9 to 14 had been associated with a perceptible reduction in the scour depth at the position of the first spur dike. Also in all the cases, the first spur dike had maximum scour depth and no longer performed similar to models No. 2 and 6. The maximum reduction in scour depth corresponds to model No. 12 although model no.11 had a considerable reduction in the maximum scour depth, too.

Considering the condition of sedimentation and also decrease in the scour depth, it could be stated that model No. 11 had acceptable and appropriate performance. The bed elevation and
flow lines around the series of spur dikes in models No. 1 and 11 are shown in Fig.9. As is seen, creating slots in the body of spur dikes totally changes the flow lines. In model No. 1, the vortex flow is formed between the spur dikes (between the first and second spur dikes, and between the second and third spur dikes) and is completely surrounded. Also, the diverted flow lines at the position of the first spur dike have greater flow interference which is due to high diversion of flow at this location. In this model, the inflow between two spur dikes ultimately exits the entrance section. But in model No. 11 the conditions are different. The vortex flow between the spur dikes in model No. 11 is smaller and is formed in between the spur dikes web and downstream wall. Also, the inflows between the two spur dikes travel a different path. Two groups of flows enter the field between the two spur dikes; the flows which enter from the slots and those which enter from the section between the two consequent spur dikes. The outflow also takes place from slots in the body of the spur dike at downstream and the section between the two consequent spur dikes. The other point seen in the flow lines of model No. 11 is that some flows enter the space between the first and second spur dikes and finally exit the third spur dike body, whereas in model No. 1 this type of flow does not exist.

5. Conclusion

Using spur dikes for controlling the erosion near the river bed, banks and paths of culverts has always been under the focus of attention. Using this structure due to the high rate of erosion around is associated with many problems and continuous research has been done for reducing the erosion and optimizing the structure performance. Using a combination of spur dikes in series is an approach that Nayyer et al. (2019) have investigated and analyzed. They ultimately introduced the LTT combination as the optimum combination of a series of 3 spur dikes to reduce the scour depth. As the utilize of numerical models to anticipate and evaluate erosion around hydraulic structures is essential in various water resource management issues, in the present research, by employing CFD model, applying this optimum combination, the effect of the presence of combined slots within the web and wing of a series of spur dikes was investigated and ultimately the (L$_{S-W-wi}$, T$_{S-W}$, T$_{S-W-wi}$) combination with slots in the web and wing of the first and third spur dike and also slot in the web of the middle (second) spur dike was selected as the best combination for reducing the scour depth and increase of sedimentation. In continuation, the other results are presented.

- The Flow-3D numerical model has been successful in modeling and analysis of the flow condition around the spur dike and erodible river. It has been capable of simulating changes in the scour depth in various combinations with high accuracy. The statistical indices values for making a comparison between the experimental and numerical results in models of this research were $R^2=0.97$, RMSE=0.28 and MAE=0.24
- Use of the slot only in the body of the first spur dike could be significantly effective in reducing the maximum scour depth. With an equal ratio of opening area to the effective area of the structure, where the slot is created in the web of the spur dike, it could reduce the scour depth at the first spur dike up to 55%. This value where the slot is created both in the web and wing of the first spur dike is 25%.
- In a condition where only the slot exists in the web and wing of the first spur dike, the ratio of sedimentation height to the total bed erosion is about 6.5% higher with respect to the case where there is no slot.
Presence of the slot in the body of the second and third spur dikes also causes a reduction in the scour depth. In the case where the slot is in the body of the second spur dike and in the web and wing of the third spur dike, sedimentation is reduced up to 52% and the ratio of the sedimentation height to the total bed erosion is increased up to 6.8%, also the maximum scour depth reduces up to 20%.

The flow condition around the spur dikes with slots is significantly different from the state that there is no slot. The inflow and outflow in the field between the spur dikes in these two states travel different paths. This issue has a considerable effect on the bed morphology.

Presence of the slot in the spur dike structure and its various positions have a complex and significant effect on the form and morphology of the erodible bed. As providing a slot in the spur dikes has positive impacts, therefore there is a need for further investigation and applying different other combinations that could be considered by other researchers.

References
Acharya, A., Duan, J.G., 2011. Three dimensional simulation of flow field around series of spur dikes. In World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability, 2085-2094.
Babar, R., Setia, S., Setia, B., 2000. Scour Protection by a Slot through a model Bridge Pier. Proceeding of International Symposium on Recent Advances in Experimental Fluid Mechanics, Indian Institute of Technology Kanpur, India.
Barbhuiya, A.K., Dey, S., 2004. Local scour at abutments: A review. Sadhana, 29(5), 449-476.
Fei-Yong, C. and Ikeda, S., 1997. Horizontal separation flows in shallow open channels with spur dikes. Journal of Hydrosience and hydraulic Engineering, 15(2), 15-30.
Chiiew, Y.M., 1992. Scour protection at bridge piers. Journal of Hydraulic Engineering, 118(9), 1260-1269.
Coleman, S.E., Lauchlan, C.S. and Melville, B.W., 2003. Clear-water scour development at bridge abutments. Journal of Hydraulic Research, 41(5), 521-531.
Dorosti, M., Shafai Bejestan, M., Amirsalarl Maymani, F., 2018. Journal of Water and Soil Science (Science and Technology of Agriculture and Natural Resources), 22(2), 67-79.
Farzin, S., Karami, H., Hajjabadi, R., Nayyer, S. and Hamzeh Ziabari, S. M. (2019). Evaluating the Effect of Various Parameters of Protective Spur Dike on Scour Depth Reduction using Group Method of Data Handling (GMDH) and Gene Expression Programming (GEP). JW 0, 0 (19) :194-203.
Flow Science, Inc., 2008. FLOW-3D User’s Manual. 9.3 ed. Los Alamos, NM: Flow Science Inc.
Gu, Z., Cao, X., Jiao, Y., and Lu, W. Z. (2016). Appropriate CFD models for simulating flow around spur dike group along urban riverways. Water Resources Management, 30(13), 4559-4570.
Hasanpour, N., Abdollahpour, M., Khosravinia, P., Hosseinzadeh Dalir, A. 2012. Effect of slot on time development around the abutments. 9th International River Engineering Conference Shahid Chamran university, 22-24 Jan, 2012, Ahwaz.
Heidarnejad, M., Bajestan, M.S. and Masjedi, A., 2010. The effect of slots on scouring around piers in different positions of 180-degrees bends. World Applied Sciences Journal, 8(7), 892-899.
Heydarpour, M., Afzalimehr, H., Khodarahmi, Z., 2007. Local Scour Protection of Circular Bridge Pier Groups Using Slot. Journal of Agricultural Sciences and Natural Resources, 14:174-185.
Hirt, C.W. and Nichols, B.D., 1981. Volume of fluid (VOF) method for the dynamics of free boundaries. Journal of computational physics, 39(1), 201-225.
Ho, J., Yeo, H.K., Coonorod, J., Ahn, W., 2007. Numerical modeling study for flow pattern changes induced by single groyne. In Proceedings of the Congress-international Association for Hydraulic Research, 32(2), 662.
Keshavarz, M.H., Hakimzade, H., Ghaldarbandi, R., 2009. Three-dimensional Numerical Simulation of Flow Pattern around the Perpendicular and Inclined Groynes with Respect to Various Boundary Conditions. Journal of Marine Engineering, 4(8), 11-24.
Kumar, M., Malik, A., 2016. 3D simulation of flow around different types of groyne using ANSYS Fluent. Imperial Journal of Interdisciplinary Research, 2(10).

Kumar, T., Tyagi, D., Aggarwal, L., Kumar, M., 2018. Comparison of scour around different shapes of groynes in open channel. International Journal of Recent Trends in Engineering and Research, 4 (3), 382-392.

Kumar, V., 1996. Reduction of scour around bridge pier using protective devices, Doctoral dissertation, PhD Thesis, University of Roorkee, Roorkee, India.

Kumar, V., Raju, K.G.R., Vital, N., 1999. Reduction of local scour around bridge piers using slots and collars. Journal of hydraulic engineering, 125(12), 1302-1305.

Lee, K.S., Jang, C.L., 2016. Numerical investigation of space effects of serial spur dikes on flow and bed changes by using Nays2D. Journal of Korea Water Resources Association, 49(3), 241-252.

Masjedi, A., Jafari, B., 2018. An investigation into the Effect of Slot in Spur Dike on the Development of Scouring Around it in a 180-Degree Bend. JWSS-Isfahan University of Technology, 22(3), 357-371.

Meymani, F., Fathi, A., mahmoodian shoooshtari, M., 2019. The effect of slot on bed topography around the bank attached triangular vane in 90-degree bend. Iranian Journal of Soil and Water Research, 48(5): 951-961.

Moncada-M, A.T., Aguirre-Pe, J., Bolivar, J.C., Flores, E.J., 2009. Scour protection of circular bridge piers with collars and slots. Journal of Hydraulic Research, 47(1), 119-126.

Monjezi, A., MASJEDI, A., Heidarnejad, M., Pourmohammadi, M.H., 2019. Experimental Study of Slot Effect on the Riprap Stability Around Spur Dike in River Bend.

Nayyer, S., Farzin, S., Karami, H., Rostami, M., 2019. A numerical and experimental investigation of the effects of combination of spur dikes in series on a flow field. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41(6), 256.

Nayyer, S., Karami, H., Farzin, S., Rostami, M. 2018. Experimental Study of Scouring Around a Simple Spur Dike under the Influence of Adjacent Spur Dikes. Iranian Journal of Irrigation and Drainage. 4(12), 840-849.

Pandey, M., Lam, W.H., Cui, Y., Khan, M.A., Singh, U.K., Ahmad, Z., 2019. Scour around Spur Dike in Sand–Gravel Mixture Bed. Water, 11(7), 1417.

Pandey, M., Valyrakis, M., Qi, M., Sharma, A. and Lodhi, A.S., 2020. Experimental assessment and prediction of temporal scour depth around a spur dike. International Journal of Sediment Research. https://doi.org/10.1016/j.ijsrc.2020.03.015.

Tafarojnoruz, A., Gaudio, R., Calomino, F., 2012. Evaluation of flow-altering countermeasures against bridge pier scour. Journal of hydraulic engineering, 138(3), 297-305.

Vaghefi, M., Faraji, B., Akbari, M., Eghbalzadeh, A., 2018. Numerical investigation of flow pattern around a T-shaped spur dike in the vicinity of attractive and repelling protective structures. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40(2), 93.

Vaghefi, M., Eghbalzadeh, A., Rostamnezhad, M., 2016. Numerical study of the effect of discharge on flow pattern around a submerged spur dike in an open channel. Water Resource Engineering, 9(28), 67-80.

Yang, J., Zhang, J., Zhang, Q., Teng, X., Chen, W., Li, X., 2019. Experimental research on the maximum backwater height in front of a permeable spur dike in the bend of a spillway chute. Water Supply, 19(6), 1841-1850.

Yeo, H.K., Kang, J.G., Kim, S.J., 2005. An experimental study on tip velocity and downstream recirculation zone of single groynes of permeability change. KSCE Journal of Civil Engineering, 9(1), 29-38.

Zamani, M., Rabieifar, H. and Rostami, M. (2021) Numerical and Experimental Investigation of the Effect of Spur Dikes Placement Position on the Hydraulic and Erosion Conditions of Lateral Intakes. Journal of Watershed Management Research, 12(24).

Zhang, H., Nakagawa, H., 2008. Scour around spur dykes: Recent advances and future researches, Annuals of the Disaster Prevention Research Institute, Kyoto University 51(Part B), 171-188.
Fig. 1. A) Experimental flume and B) geometric parameters of the spur dikes.

Fig. 2. A) 3D view of geometry and boundary conditions, B) solution meshing used in the numerical model.

Fig. 3. Eroded Bed A) experimental model of Nayyer et al. (2019), B) scour depth in the present research numerical model.

Fig. 4. A) geometry of the spur dikes and their slots, B) slot characteristics and position of it in the spur dike web, C) position of the slot in spur dike web and wing in L-shaped spur dike.
Fig. 5. Comparison between the equilibrium scour depth values in the experimental and numerical models.

Fig. 6. Temporal changes of the scour depth in LTT combination.

Fig. 7. Changes in the mean scour depth and ratio of sedimentation to erosion.

Fig. 8. Bed level in models No. 4 and 8.
**Fig. 9.** Results of simulation for models No. 1 and 11: A) - Changes in the bed, B) stream lines, C) Cross section at tip of the first spur dike

| Test ID | Q (lit/s) | $U/U_{cr}$ | $d_s/\bar{y}$ | $d_{s2}/\bar{y}$ | $d_{s3}/\bar{y}$ | $d_{save}/\bar{y}$ |
|---------|-----------|-------------|----------------|------------------|------------------|------------------|
| TTT     | 28.5      | 0.95        | 2.75           | 0.95             | 0.53             | 1.41             |
| LTT     |           |             | 2.7            | 0.6              | 0.3              | 1.21             |
### Table 2
Statistical comparison of scour depth for the experimental and numerical results (LTT combination)

| Turbulence Model | R²  | RMSE | MAE |
|------------------|-----|------|-----|
| RNG k–ε          | 0.97| 0.66 | 0.19|
| K–ε              | 0.99| 0.12 | 0.03|
| LES              | 0.90| 1.47 | 0.43|

### Table 3
Characteristics of the used models in the present study

| Model ID | Discharge (l/s) | First Spur Dike | Second Spur Dike | Third Spur Dike |
|----------|-----------------|-----------------|------------------|-----------------|
| 1        | 28.5            | L               | T                | T               |
| 2        | 28.5            | L,s,w           | T                | T               |
| 3        | 28.5            | L,s,w           | T                | T               |
| 4        | 28.5            | L,s,w           | T                | T               |
| 5        | 25.65           | L               | T                | T               |
| 6        | 25.65           | L,s,w           | T                | T               |
| 7        | 25.65           | L,s,w           | T                | T               |
| 8        | 25.65           | L,s,w           | T                | T               |
| 9        | 28.5            | L,s,w           | T_s,w           | T               |
| 10       | 28.5            | L,s,w           | T_s,w           | T_s,w           |
| 11       | 28.5            | L,s,w           | T_s,w           | T_s,w           |
| 12       | 28.5            | L,s,w           | T_s,w,w_i       | T               |
| 13       | 28.5            | L,s,w           | T_s,w,w_i       | T_s,w           |
| 14       | 28.5            | L,s,w           | T_s,w,w_i       | T_s,w,w_i       |

### Table 4
Changes in the bed in models with slots with respect to the state of no slot.

| Model ID | Sediment (%) | Scour (%) | Sediment/Scour (%) | Maximum scour depth (%) | Max scour depth location |
|----------|--------------|-----------|--------------------|-------------------------|------------------------|
| 9        | 32           | -5        | 6.1                | -21                     | at tip of first spur dike |
| 10       | 15           | -6        | 5.3                | -13                     | at tip of first spur dike |
| 11       | 52           | -3        | 6.8                | -20                     | at tip of first spur dike |
| 12       | 29           | -4        | 5.8                | -23                     | at tip of first spur dike |
| 13       | 32           | -6        | 6.0                | -15                     | at tip of first spur dike |
| 14       | 52           | -2        | 6.7                | -15                     | at tip of first spur dike |