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Hydraulic Simulation of Flow Around Spur Dikes

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Abstract: ***The morphological changes of rivers, which are manifested by bed and banks deformations, show a direct relationship with water flow and sediment transport. Spur dikes are among the most common structures used to regulate velocity distribution and control sedimentation in a river section. This paper aims to simulate the hydraulic properties of steady turbulent flow in a straight rectangular open channel which has spur dikes with various configurations, such as number, alignment and lengths. The effects of the spur dikes on the velocity distribution have been evaluated three-dimensional (3D) Computational Fluid Dynamic (CFD) method. The simulated results from the model are calibrated and validated using data obtained from physical model. Different scenarios with spur dikes were simulated, and the results were demonstrated using the isovels, velocity magnitudes and mass exchange between spur dikes fields and main flow. Eventually, each scenario gives a better understanding on employing spur dikes for river restoration, enhancing navigation (by increasing water depth and rearranging the thalweg line), and protecting abutments and pump intakes against erosion as well as creating stable aquatic habitat.***

Index Terms: Hydraulic simulation, velocity distribution, spur dike, river restoration.

I. INTRODUCTION

Spur dike is a structure used in rivers as well as in marines as a barrier extending from bank or shore to divert the flow away, or to control the velocity distribution. In addition, it is considered as one of the most familiar structures in river restoration due to its ease of construction from natural available material, or the large variety of designs to serve one or more purposes at the same time. The main aim for deflecting the current from the banks are to provide water depth in the main stream for navigation as well as to protect floodplain against extra flow during flood season by increasing the relative ability to pass flow [10], protect banks from erosion that causes land contraction and excessive sedimentation as well as water quality degradation [7]. The spur dikes can also divert the highest velocity away from bridge piers, pumps or river confluence that cause erosion. They are also useful in restoring flora and fauna environments against current fluctuations [16], enhance aquatic habitats by provide a stable pool in unstable rivers in between the successive spur dikes (called dead zone), between the successive spur dikes (called dead zone), [13] and [5].

Previous studies have concentrated on maximum scour depth around the dikes by trying to correlate scour depth as a function of main flow and geometrical features, obtained from small scale laboratory experiments [11]. On the other side, the intensive turbulent flow field that occurs around some structures such as spur dikes, bridge pier and abutment to predict scouring has been studies, [4], the same way to compute the scour has been adopted by locating recirculating region that occurs just upstream of the spur dike, [3]. The interaction between spur dikes fields and the hydrodynamic field has been examined as a physical model, [20], [12] or as numerical studies [14]. For velocity distribution observed by using a 3D Acoustic Doppler Velocimeter (ADV) within and around one of the fields between two spur dikes in conditions of low and high flow to analyze the turbulent kinetic energy (TKE) has been achieved by [5]. While, [19] had performed two-dimensional depth averaged Large Eddy Simulations (LES) for flow near arrays of submerged and non-submerged spur dikes. Three-dimensional LES was examined by [6] for flow and mass exchange passed through an infinite series of non-submerged spur dikes as well as [8] and [9] studied the situation of a single embayment (two non-submerged and two submerged spur dikes), respectively. Enhancing the species habitat have been studied by [2] as two dimensional hydraulic simulations to measure the short and long term effects of spur dikes on weighted usable area.

There is considerable attention and debate on the way to optimize the efficiency of using various geometrical properties of spur dikes regarding the shape, distance, and inclination, in order to compute and analyze the flow velocity distributions at the vicinity of spur dikes by employing a numerical simulation. Which is the main aim of this study. To achieve that, three dimensional CHEN-KIM (K-ε) turbulence model with fixed bed has been used and validated with the results obtained from physical modelling, while, few studies have been carried out in this subject, but mainly were focused on the scour that occurs at the tip of the first dike or sediment exchange between the main flow and dead zone.

II. MATERIALS AND METHODS

A. Experimental Set-Up

All the tests in this study were performed in a recirculating flume with a rectangular cross section and moveable bed with dimensions of 19.0 m long, 1.5 m wide, and 0.7 m deep located at the Hydraulic Laboratory, Mosul University, Iraq.

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A test section of 7 m length which it located at the middle of the flume was selected for conducting the experiments. Flow rate in the flume was measured using a submerged weir located at the end of the channel.

Flow depth was controlled by sluice gate located downstream of the test section and the water surface and bed profiles had been observed at grid points as shown in Fig. 1(a).

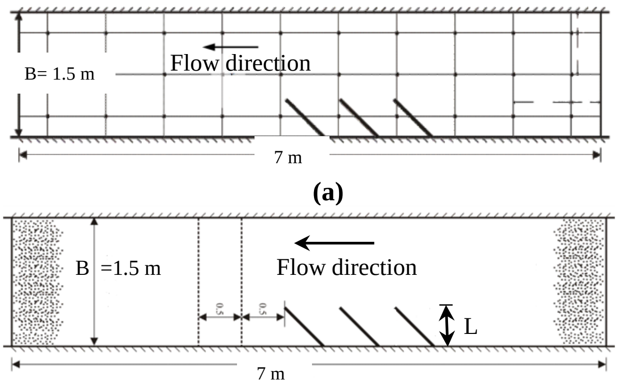

Fig. 1: (a) The Grid Points for Bed and Surface Profiles in the study Domain, (b) the Locations of Velocity Measurements.

Care was taken to assure the flow depth and discharge remained constant as 17.5 cm and 0.065 m^3/sec respectively. In this study, velocity distribution is considered as one of the most important measurements. It was observed at two sections located at 0.5 m and 1.0 m downstream of the spur dikes, as shown in Fig.1 (b). The observations were conducted at selected points by using available Pitot-static tube device.

The bed of the approach flow section was horizontal and covered by 20 cm depth of sand which is classified as very course sand (D_{50} =1.46 mm).

The spur dike models are thin in cross-section with thickness 2 cm made of wood and they are non-submerged. Their geometrical properties are the number of spur dikes which are 1, 2 or 3, and inclination angle of 45° against the flow direction, 90° (perpendicular) and 135°. The length of the structures that extend into the main stream provide contraction ratio (L/B) equal to 40 %, 30% or 20%, in which L is the projected length and B is the channel width (Fig. 1 (b)). The total number of experiments was 9, all tests are under the same hydraulic conditions.

B. Theoretical – CFD Simulation

The CFD model selected for this study can simulate three dimensional model. The governing equation that is involved in the model is Navier-Stokes equation for incompressible fluid.

A uniform computational fine mesh was adopted within a rectangular coordinate system to provide adequate discretization for the spur dike geometry as well as the whole domain. To initialize the model, mean approach velocity of 0.25 m/s, and flow depth of 0.175 m were entered as input data to CFD model. All the geometric details included in the simulation were the same as the physical model. The inflow boundary was assumed to have a known uniform velocity. An outflow boundary with no re-entry of the fluid condition was used at the downstream boundary. Wall boundary was applied to the bed and side walls which were all considered as same material with fixed bed. Simulations were run for long period until the flow field reached the steady state condition. In the present investigation, a comparative study of CHEN-KIM (K-ε) turbulence model (which is modified from RANG model and has new constants based on comparison with experimental data) was made to analyse flow field around the spur dikes and the computed results are compared with the experimental results.

After calibration, many simulations have been tested but included into two parts, the first part use details from the experiments (9 tests) to generate the 3D velocity distribution over the simulated channel. Those measurements cannot be taken from the physical model due to limited facilities. The second part generate new scenarios which are more complicated due to intensive configuration for the structures (another 25 tests), which represent another design of spur dikes like L shape and T-shape which have been used individually or combined with the normal design as a series.

III. RESULTS AND DISCUSSION

A. Comparison between Physical and Numerical Models

The lateral velocity distributions of flow in two sections downstream of the spur dikes are compared with the measurements obtained from experiments to select the more accurate turbulence model for producing three dimensional flow field around the structures. The numerical results gave a reasonable agreement with the measured data. The mean absolute error between both values is less than 5%. Selected results from the calibration process are presented in Fig. 2.

Most of the measured and simulated horizontal velocity profile match very well at all points along the water depth except that located near the bed in which it was found distinctly different. The difference was found slightly increased towards downstream. The velocity overestimation may be due to errors in both physical and numerical models, which are: (1) it is moveable bed in experiments but fixed in the numerical model, (2) The error in velocity measurement near the bed, which is supported by the findings of [17], and (3) the numerical model can simulate the turbulent interaction of the flow accurately except the region closer to bed or side walls.

B. Simulation Studies

Based on the acceptability of the simulation as shown above, further analysis has been performed to investigate the effect of using the spur dikes in a channel for three different considerations: navigation, aquatic habitat and protecting other structures.

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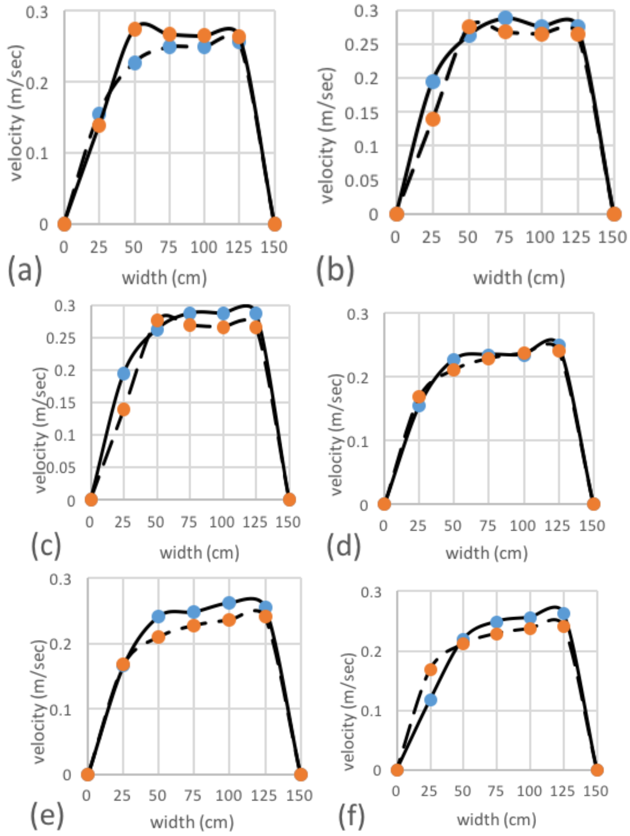

Fig. (2): Comparison of velocity distribution from physical and numerical models at different and locations.

(a): 0.5 m after last dike at 9 cm water depth; (b): 0.5 m after last dike at 12 cm water depth; (c): 0.5 m after last dike at 15 cm water depth; (d): 1.0 m after last dike at 6 cm water depth; (e): 1.0 m after last dike at 9 cm water depth; (f) : 1.0 m after last dike at 12 cm water depth.

1. Improving Navigability

The common usage of spur dike is to improve river navigability, by deepen the flow depth in the main stream and rearrange the Thalweg line. When a spur dike is constructed in an open channel, the flow becomes highly disturbed. Two kinds of vortices form near the spur dike, the first one is vertical and the other transverse vortices, [18]. The vertical vortices are formed at the nose of the structure due to the lateral flow parallel to the length of the spur dike field within the main stream region, while the transverse vortices are formed because of the flow downstream the spur dike. The interaction of those two types of vortices produce a highly 3D flow near the spur dike fields. Due to this movement of flow, it is expected to increase velocities in the region of main channel just beyond the end of the spur dike nose and decreased velocities immediately upstream and downstream from the spur dike fields, Fig. 4.

Sediment transported from one region to another by flowing water. Depending on the particular size of sediment and flow intensity, the amount of sediment transported proportionally increased with the flow velocity. All natural streams with erodible bed and banks have a tendency to turn to meandering channels. Many factors including discharge, sediment load, bed slope, and composition of bed and banks affect the sinuosity of the natural stream, unless the channel is resisted by training works.

In the case of river navigability, spur dike is a structure used to provide the sufficient requirements for navigation in both flow depth and channel alignment. It can also be used to deflect the flow direction toward a desirable point within a channel [1].

In order to obtain a well-defined straight and deep channel to enhance navigation, the recommended space between spur dikes is 1.5-2 times the spur dike length [21]. The number of dikes should be distributed along the part of the channel that need to be restored, while the length of the spur is consider a function of the main velocity in the channel which must be greater than the critical velocity to erode the bed material. The perpendicular spur dikes are the best design for this purpose because they create higher velocity in the main stream, but if the excessive scouring occurs at the nose the first dikes that can lead to channel stability issues. To overcome this issue, it can be replaced by spur dike having L shape which can reduce the scouring at it head, as shown in Fig (3). Thalweg line adjustment can be improved by using different lengths of dikes in sequence, in another words to push away the greatest depth from one bank to another as illustrated in Fig (4).

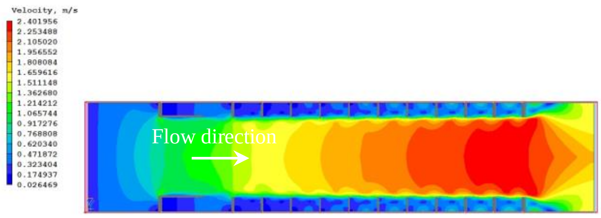

Fig. 3: Longitudinal Velocity Distribution for 11 Perpendicular Spur Dikes Each Bank Started with L Shape Dike, The Distance between each is 40 cm and the Length is 20 cm, for Water Depth Increasing.

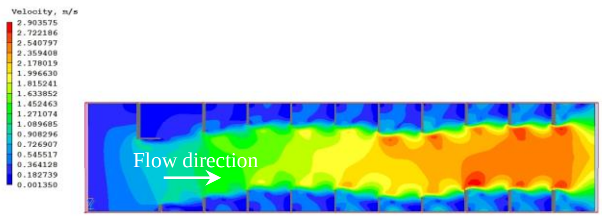

Fig. 4: Longitudinal Velocity Distribution for 10 Perpendicular Spur Dikes Each Bank Started with L shape dike in one bank, the distance between each is 60 cm and the length is Various from 10-40 cm, for Thalweg Line Alignment.

2. Enhancing Aquatic Habitat

The main method to enhance the ecosystem in a river is to create a stable pool in unstable rivers due to seasonal fluctuations in discharge as well as velocity distribution, that reduce nutrients required for some species. The created pools will accelerate or preserve the growth rate of phytoplankton and reproduction in proportion to suspended load deposition. This condition should exist in between any sequent spur dikes to create local shelters for various kinds of flora and fauna [15].

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The recommended space between spur dikes is 2 to 6 times the spur dike length for good aquatic habitat, [21].

Using spur dikes in the stream for this purpose will associated with other undesirable change such as scouring at the nose of the structure or erosion in the facing bank. The best design of the spur dike in the channel will be in series of them aligned with the downstream direction as shown in Fig. (5), and the extending length or the distance between them is a function of the grain size of the suspended sediment available due to low velocity provided (low velocity has been provided with narrowest spur dike fields). To create specific local habitat, T-shape spur dike is one of the best choices due to its creates a long zone of low velocity, as shown in Fig. 6.

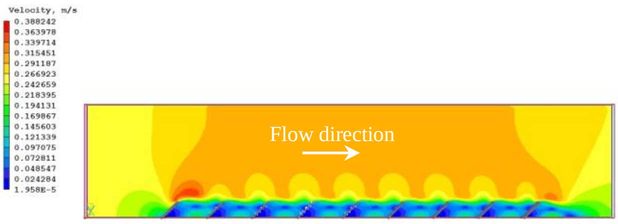

Fig. 5: Longitudinal Velocity Distribution for 9 Spur Dikes with 45º angle, the Distance Between Each Spur Dike is 60 cm and the length is 30 cm, for Improving the Habitat.

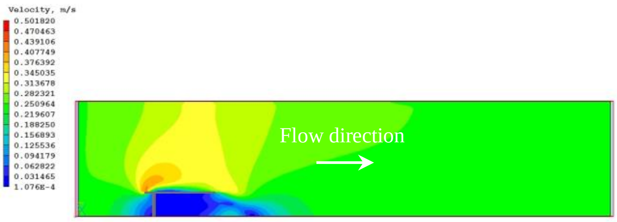

Fig. 6: T-Shape Spur Dikes, the Length is 90 cm and 30 cm Extending Length, for Improving the Habitat.

3. Protecting Other Structures

Spur dikes can be designed to protect various structures such as bridge abutments and pump intakes for water supply or irrigation projects, because those structures are considered an obstacle into the main flow, and the flow causes scouring near them, then their efficiency would be reduced with flow decay.

Compared with other river training structures, such as revetments, spur dikes are among the most economical structures that may be used for erosion protection, [15]. A single spur dike can also be used to deflect the flow toward a desirable point in a channel. Fig. (7) illustrates the 45º single spur dike that could be constructed before the structure which needs protection or 135º single spur dike after the structure. Fig. (8) shows its impact to reduce the flow velocity in its vicinity with a minimum effect on the main flow.

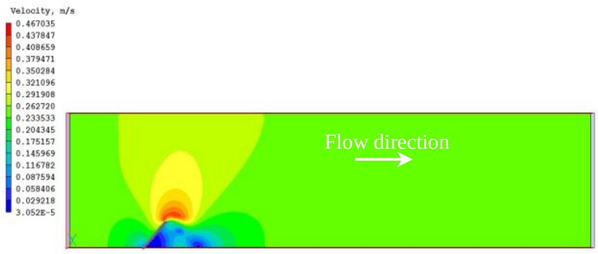

Fig. 7: Longitudinal Velocity Distribution for 45º Single Spur Dike, the Length is 42, for Protecting Purpose.

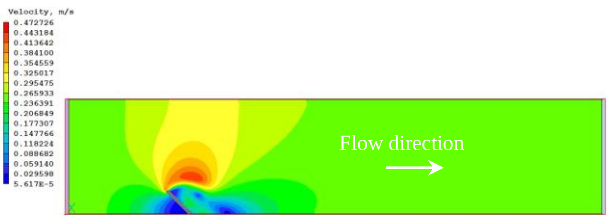

Fig. 8: Longitudinal Velocity Distribution for 135º Single Spur Dike, the length is 42, for Protecting Purpose.

IV. CONCLUSION

The mutual relationship between sediment transport and velocity distribution in any natural stream give flexibility to the engineers to control one of them in order to improve the channel geometry, spur dike is used commonly for that purpose by deflecting the flow to desirable side.

In this study, theoretical simulation (CHEN-KIM K-ε turbulence model) was used, then validates it with the experiments, to simulate how spur dikes can be used in to improve its usability such as navigation, enhancing the aquatic habitat or protecting other structures in the river. Various geometric properties and configurations of spur dikes were studied to find the suitable conditions for situation. This model showed good agreements with the experiments, for that its recommended for further studies of hydraulic performance around spur dikes.

To provide flow depth for navigation, the depth in the main stream can be increased by constructing perpendicular spur dikes at both banks with the distance of 1.5-2 times between them. For realigning the thalweg line, different lengths of spur dikes in each bank with the same contraction rate have to be used. Providing low velocity in unstable streams is the main condition to flourish the riverine ecosystem, which can occur in between a series of spur dikes with alignment arranged in the flow direction and having at least a space equal twice the spur dike length.

For protecting purposes, a single spur dike which is aligned appropriately can be applied to prevent excessive scour at the protected structure in the river.

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