SIMULATION OF THE EFFECTS OF BANK VEGETATION ON VELOCITY PROFILES IN A MEANDERING COMPOUND CHANNEL

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ABSTRACT

Advances in computing and simulation capability increase interest in using computational fluid dynamics to solve complex flow structures in meandering compound channel. Highly complex and three-dimensional flows inside the meandering compound channel with the presence of vegetation are still not fully comprehend. The aim of the research is mainly to simulate the effects of bank vegetation on velocity profiles inside the meandering compound channel using computational fluid dynamic models. An existing meandering compound channel at Hydraulics and Hydrology Laboratory, Universiti Teknologi Malaysia was modelled numerically. TELEMAC-2D (two-dimensional) model and TELEMAC-3D (three-dimensional) model were used to simulate hydrodynamics pattern inside the main channel and floodplain with and without existence of bank vegetation. Both models use the same horizontal unstructured triangular meshes of the meandering compound channel. Simulations were computed for different relative depths (DR) and vegetation spacing of 2-, 4- and 8-times the vegetation diameter (d). Models were calibrated using the roughness coefficient and validated using streamwise velocity profiles at the apex sections. Velocity components between modelled and measured were discussed at selected cross-sections inside the meandering compound channel. Significant reductions of depth-averaged streamwise velocity at the outer bend were 69.9% (DR0.30) and 71.4% (DR0.45) for 2-times diameter (2d) vegetation spacing. The three-dimensional model also shows that streamwise velocity reduction for overbank flows at the outer bend of 83.3% (DR0.30) and 72.2% (DR0.45). Depth-averaged streamwise velocity at the inner bend shows an increase of 51.4% (DR0.30) and 58.4% (DR0.45). The streamwise velocity increases 3.2 times (DR0.30) and 4 times (DR0.45) from the three-dimensional results at the same inner bend. This is because vegetation protects and reduces the velocity of overbank flows at the outer bend while it increases the velocity at the inner bend by blocking and redirect the overbank flows into the direction of the main channel. Vertically averaged velocity from TELEMAC-3D shows difference of less than 15% between simulated and measured inside the main channel. However, TELEMAC-2D gives a higher difference of up to 3.8 times than measured velocity at cross-over regions. The high percentage of differences is believed to be due to three-dimensional interactions inside the cross-over regions from the interactions between overbank and inbank flows. The presence of vegetation significantly increased the level of complexity in cross-over regions, which contributed to high difference between model and measurement. In computational model, the effects are more significant during low relative depth. As the distances between vegetation increases, velocity patterns inside the meandering channel tends to resemble non-vegetation conditions. Both two- and three-dimensional model also predicted the same velocity patterns. In conclusion, TELEMAC-2D and TELEMAC-3D show the ability to simulate flow properties inside the meandering compound channel with and without vegetation.

ABSTRAK

Kemajuan dalam pengkomputeran dan keupayaan simulasi meningkatkan minat untuk menggunakan perkomputeran dinamik bendalir untuk menyelesaikan struktur aliran kompleks dalam saluran majmuk berliku. Aliran yang sangat kompleks dan tiga-dimensi dalam saluran majmuk berliku dengan kehadiran tumbuh-tumbuhan masih belum difahami sepenuhnya. Tujuan utama kajian ini adalah untuk mensimulasikan kesan wujudnya tumbuh-tumbuhan tebing terhadap profil halaju dalam saluran majmuk berliku menggunakan model perkomputeran dinamik bendalir. Saluran majmuk berliku yang sedia ada di Makmal Hidraulik dan Hidrologi, Universiti Teknologi Malaysia telah dimodelkan secara berangka. Model TELEMAC-2D (dua-dimensi) dan model TELEMAC-3D (tiga-dimensi) digunakan untuk simulasi corak hidrodinamik dalam saluran utama dan dataran banjir dengan dan tanpa kewujudan tumbuh-tumbuhan tebing. Kedua-dua model menggunakan jejaring mendatar segitiga tidak berstruktur yang sama daripada saluran majmuk berliku. Simulasi dijalankan untuk kedalaman relatif (DR) yang berbeza dan jarak tumbuh-tumbuhan 2-, 4- dan 8-kali diameter (d) tumbuhan. Model ditentukur menggunakan pekali kekasaran dan disahkan menggunakan profil halaju mengikut aliran saluran utama di keratan rentas apeks. Komponen halaju antara model dan ukuran adalah dibincangkan pada keratan-rentas terpilih didalam saluran majmuk berliku. Pengurangan ketara halaju purata-kedalaman mengikut aliran saluran utama di liku luar adalah 69.9% (DR0.30) dan 71.4% (DR0.45) untuk 2-kali diameter (2d) penjarakan tumbuhan. Model tiga-dimensi turut menunjukkan pengurangan halaju mengikut aliran saluran utama untuk aliran lampau tebing di liku luar 83.3% (DR0.30) dan 72.2% (DR0.45). Halaju purata-kedalaman mengikut aliran saluran utama di liku dalam pula menunjukkan peningkatan 51.4% (DR0.30) dan 58.4% (DR0.45). Halaju aliran mengikut saluran utama meningkat 3.2 kali (DR0.30) dan 4 kali (DR0.45) ganda dari hasil tiga-dimensi pada liku dalam yang sama. Ini kerana tumbuh-tumbuhan melindungi dan mengurangkan halaju aliran lampau tebing di liku luar sementara ia meningkatkan halaju di liku dalam dengan menyekat dan mengubah arah aliran lampau tebing mengikut saluran utama. Halaju purata menegak dari TELEMAC-3D menunjukkan perbezaan kurang daripada 15% antara yang disimulasi dan diukur di dalam saluran utama. Walau bagaimanapun, TELEMAC-2D memberikan perbezaan yang lebih tinggi hingga 3.8 kali daripada halaju yang diukur di kawasan lintasan. Peratusan perbezaan yang tinggi dipercayai disebabkan oleh interaksi tiga-dimensi dalam kawasan lintasan daripada interaksi antara aliran lampau tebing dan dalam tebing. Kehadiran tumbuh-tumbuhan dengan ketara meningkatkan tahap kerumitan di dalam kawasan lintasan, yang mana menyumbang kepada perbezaan antara model dan ukuran. Dalam model pengkomputeran, kesannya adalah lebih ketara semasa kedalaman relatif rendah. Semakin jauh jarak antara tumbuh-tumbuhan, corak halaju dalam saluran berliku cenderung menyerupai keadaan tanpa tumbuhan. Kedua-dua model dua-dimensi dan tiga-dimensi juga meramalkan corak halaju yang sama. Kesimpulannya, TELEMAC-2D dan TELEMAC-3D menunjukkan kemampuan mensimulasikan sifat aliran dalam saluran majmuk berliku dengan dan tanpa tumbuh-tumbuhan.

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LIST OF ABBREVIATIONS

2D	-	Two-dimensional
3D	-	Three-dimensional
ADV	-	Acoustic Doppler Velocimeter
CFD	-	Computational Fluid Dynamics
DR	-	Relative depth
LDA	-	Laser Doppler Anemometer
LES	-	Large Eddy Simulation
RHS	-	right-hand side
RSM	-	Reynolds stress model
SUPG	-	Streamline upwind Petrov-Galerkin
UTM	-	Universiti Teknologi Malaysia
nv	-	non-vegetation
2d	-	2 times vegetation diameter distance from vegetation centre to centre
4d	-	4 times vegetation diameter distance from vegetation centre to centre
8d	-	8 times vegetation diameter distance from vegetation centre to centre
S1	-	Section 1
S4	-	Section 4
S8	-	Section 8
S12	-	Section 12
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LIST OF SYMBOLS

A	-	Area of water flow
B	-	Width of main channel
C_D	-	Drag coefficient
d	-	Diameter of rod or vegetation
DR	-	Relative depth or depth ratio
F_i	-	Body force in x_i direction
f	-	A variable in TELEMAC solution algorithm
g	-	Gravitational acceleration (= 9.81 m/s2)
H	-	Total water depth, water depth in main channel
h	-	Water depth
h_{mc}	-	Depth of main channel
i, j	-	Standard tensor indices varying between 1 and 3
k	-	Turbulent kinetic energy
k_s	-	Roughness height
L	-	Distance or rod spacing from vegetation centre to centre
n	-	Manning's coefficient of roughness
n	-	Frictional step
nv	-	Normal vector
P	-	Global pressure
p	-	Instantaneous pressure
p'	-	Pressure turbulent fluctuation
Q	-	Flow discharge or flow rate
S	-	Free surface
S_o	-	Channel bed slope
S	-	Salinity
T	-	Temperature
t	-	time
t_0	-	Initial time
t_s	-	Time step
$\boldsymbol{U}$	-	Vector velocity field in cartesian space

$\boldsymbol{U}_d$	-	Depth-averaged velocity vector in cartesian space
U^S	-	Velocity at surface
U^{z_b}	-	Velocity at bottom
u',v',w'	-	Fluctuating component of velocity in x, y and z direction
u, U	-	Streamwise velocity
U_f	-	Streamwise velocity following the direction of floodplain
U_s	-	Sectional mean velocity
U_d	-	Depth-averaged velocity in x direction of curvilinear space
U_{dx}	-	Depth-averaged velocity in x direction of cartesian space
U/U_s	-	Normalised streamwise velocity to sectional mean velocity
$\overline{u_i'u_j'}$	-	Turbulent Reynolds stresses
v,V	-	Transverse or lateral velocity
V_d	-	Depth-averaged velocity in y direction of curvilinear space
V_{dx}	-	Depth-averaged velocity in y direction of cartesian space
V/U_s	-	Normalised transverse velocity to sectional mean velocity
W	-	Vertical velocity
W/U_s	-	Normalised vertical velocity to sectional mean velocity
x	-	Longitudinal or streamwise direction in curvilinear coordinate of main channel
X	-	Longitudinal or streamwise direction of compound channel
y	-	Lateral or transverse direction in curvilinear coordinate of main channel
Y	-	Lateral or transverse direction of compound channel
z, Z	-	Vertical direction
z_b	-	Bottom elevation
ρ	-	Fluid density
ρ_0	-	Constant, average, reference fluid density
$\Delta\rho$	-	Variation of fluid density
τ_b	-	Boundary or bed shear stress
τ_{ij}	-	viscous stress for laminar flows
θ	-	Main channel sinuosity or circular arc of meander main channel
$\nabla\cdot$	-	Divergence

υ_t	-	Turbulent eddy viscosity
ε	-	Energy dissipation rate
ω	-	Specific dissipation rate

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CHAPTER 1

INTRODUCTION

1.1 Background of Problem

The occurrence of river flooding is a common feature in many countries. It can have tremendous consequences for communities, frequently resulting in considerable damage to property and occasionally, loss of life. The financial implications are devastating. Therefore, it is vital to have efficient floodplain and river management which will benefit communities and at the same time, will maintain the balance of the natural environment.

One of the environmentally attractive types of flood alleviation schemes is the meandering two-stage river. This system consists of a meander main channel, which carries the low discharge at all the time, and floodplains, to carry the increased flow in times of flood. Leaving floodplains areas as it is are not significant regarding economic aspects, and sometimes, the natural forms floodplains were already sustaining life not only for humans but also for animals.

About 9 % area in Malaysia have a high risk of flood occurrences., According to Othman (2013), in this area alone, about 5.7 million people are lives and makes their living there. It is a significant amount considering the number is about 18 % of the total population in Malaysia. Physical investigations on meandering compound channel required large amount of resources such as time, money and workforce. Numerical or computational method has emerged as significant tools that help researchers and engineers to simulate the flow mechanism and behaviours of this two-stage channel.

Vegetation properties and arrangements in the works by Ibrahim (2015) were considered to simulate computationally using an open source Computational Fluid Dynamics (CFD) tool known as TELEMAC. The computational results are hoped to give better insight and understanding of flow behaviours and mechanism inside the vegetated meandering compound channel.

1.2 Statement of Problem

Experimental work by Ibrahim (2015) on a model of meandering compound channel was done physically at the Hydraulic and Hydrology Laboratory, Universiti Teknologi Malaysia in Skudai, Johor. The physical model consists of one meander main channel with straight boundary floodplains at both sides. The meander main channel was built with three and one-quarter of wavelength with assumptions that flows have fully developed in the measurement area. Data were collected at five different cross-sections in the compound channel during uniform flow. Experimentation works considered non-vegetated and vegetated floodplain at two different relative depths with overbank conditions.

The data were collected only during the uniform flow where the slopes of the flow surface to be the same with the channel slope. The data collected are discharge, water level and velocity components. The discharges were measured using a digital flow meter at the channel upstream. Water level were measured with digital point gauge, and the velocity components were measured using Acoustic Doppler Velocimeter (ADV). Further details of physical experiment data collections can be found in the works by Ibrahim (2015).

Limitation by measuring devices to measure velocity profiles 5cm below the water surface makes it difficult to extract the velocity profiles near the surface, especially on the floodplains at low relative depth. Almost no measured data available for overbank flows at low relative depth and large sections of overbank flows for high relative depth. ADV also have difficulties measuring data within 3cm from the vertical wall of main channel.

This limitation by ADV makes it challenging to measure overbank flows near vegetation. Close vegetation arrangements on the floodplain make it difficult for the measuring device to measure velocity profiles near vegetation. The presence of bank vegetation significantly contributes to the interactions between main channel and floodplain flows since it places along the meander main channel.

The behaviour of vegetated floodplains are complex, highly three-dimensional and turbulent; measuring ones in details will request a significant amount of resources and sometimes very dangerous. Details measurement near the vegetation are substantial to investigate the effects of vegetation on velocities inside the meandering compound channel.

The uses of CFD tools were considered to simulated the same physical conditions of the experimental works by Ibrahim (2015) with the aims that those tools use can reproducing the velocity profiles similarly in those limited areas. A computational method for open channel are required as an alternative to investigating further these complex interactions of flow mechanism inside the meandering compound channel.

1.3 Objectives of Research

The aim of the research is to understand primary flows distributions in meandering channels with overbank flows for different relative depths and vegetation spacing using TELEMAC modules. The detailed research objectives are as follows:

(i) To access the capability of computational models in reproducing the primary flow characteristics for overbank conditions as observed from experimental data inside the meandering compound channel.

(ii) To find out the relationship of different relative depths to the flow mechanisms by considering computational results on the non- and vegetated compound channel.

(iii) To investigate the effects of bank vegetation on velocity profiles for inbank and overbank flows from different vegetation spacing placed along the meander main channel during floods.

(iv) To compare velocity predictions between the two-dimensional and three-dimensional model from TELEMAC modules with measured for the depth-averaged velocity with and without the presence of vegetation.

1.4 Scope of Research

The physical study involves construction of a physical model with a meander main channel and floodplains on both sides. Details on the physical model can refer to the work of Ibrahim (2015). The meandering compound channel then modelled numerically based on the actual physical model.

The research uses TELEMAC modules that consist of a two-dimensional model, TELEMAC-2D and a three-dimensional model, TELEMAC-3D. Numerical modelling using TELEMAC solves free surface problems using finite element methods. Both models use the same unstructured triangular meshes generated horizontally over the compound channel. Meshes generated denser meshes in the area near the vegetation to capture in details the effects of vegetation.

Bank vegetation along the meander main channel presents by a series of islands in the computational model rather than using the roughness coefficient. Arrangements and vegetation spacing properties follow the set-up from Ibrahim (2015) physical experiments. Overbank flows conditions of the non-vegetated and vegetated floodplain with vegetation spacing of 2-, 4- and 8-times the vegetation diameter are considered for the simulation.

The computational model also simulates for two relative depth conditions; at a low relative depth of DR0.30 and a high relative depth of DR0.45. Computational results are inter-comparisons with measurement data at selected measurement cross-section inside the meandering compound channel. Comparisons between computational results of TELEMAC-2D and TELEMAC-3D were among the interest of the research. The numerical investigations on flow mechanisms cover primary velocity of streamwise, lateral and vertical, secondary flow circulations and comparisons between the two- and three-dimensional models.

1.5 Significance of Research

The significant occurrence of floods forced humans to tolerate and learn to live with it rather than losing those limited lands on the floodplains. People start learning to manage the river ecosystem to minimise losses from flood events and optimise land usage on the floodplains. For countries like Malaysia where plantations are among the major income generation, large-scale oil palm plantations can be observed even on the floodplains. Knowledge enhancement on the effects of vegetation planted on the floodplains to flow structures is associated with bed shear stress, indicating erosion and sedimentation process inside the compound channel.

Turbulence generated from the presence of vegetation anticipates to increases the turbulence intensities inside the meandering channel. Turbulence has significant effects on energy losses. The changes in energy losses would result in changes in flow resistance that affecting the conveyance, stage-discharge, drag force, bedforms and sediment transport behaviours, as indicates by Ismail (2007).

Any changes on the meandering channel physical parameters would restart the whole laborious data collection process all over again. Introduction to CFD can significantly tackle the challenges of using physical experiment on the meandering compound channel, given that the model firstly calibrated and validated with the experimental data.

The research findings can be taken as input or guidelines in the decision-making process for better river management practices of the meandering compound channel. These will also give more knowledge and information to researchers and engineers in designing an environmental friendly flood alleviation scheme near future.

1.6 Thesis Organisation

The thesis is organised in five chapters. Chapter 1 gives the research background which includes the problem statement, objectives, scopes and research significances. Chapter 2 presents the literature review on the flow structures of meandering compound channels, an introduction to CFD and vegetation in the open channel. The thesis research methodology includes physical experimental set-up, solution sequences, calibration, and validation of the computational model described in Chapter 3. Chapter 4 provides the computational study results of primary velocity structures in the non-vegetated and vegetated meandering compound channel. The discussions focus on streamwise velocity, lateral velocity, vertical velocity, secondary flow circulations and comparisons between TELEMAC modules. Finally, the conclusions on the findings and recommendations for future research highlighted in Chapter 5.

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LIST OF PUBLICATIONS

Indexed Journal

1. **Lim, A. H. A. S.**, Ismail, Z., Jamal, M. H. & Jumain, M. (2018). Vertical profiles of stream wise velocity inside non- and vegetated meandering compound channel. *ARPN Journal of Engineering and Applied Sciences,* 13(7). http://www.arpnjournals.org/jeas/research_papers/rp_2018/jeas_0418_6940.pdf. **(Indexed by SCOPUS)**

2. **Lim, A. H. A. S.**, Ismail, Z., Jamal, M. H. & Makhtar, M. R. (2018). Simulations of depth-averaged streamwise velocity of meandering compound channel using TELEMAC modules. *E3S Web of Conferences*. 65(07001). https://doi.org/10.1051/e3sconf/20186507001. **(Indexed by Web of Science, SCOPUS)**

3. **Lim, A. H. A. S.**, Ismail, Z., Jamal, M. H., Ibrahim, Z. & Jumain, M. (2019). Depth-averaged modelling of vegetated meandering compound channel. *IOP Conference Series: Earth and Environmental Science*. 220(012038). https://doi.org/10.1088/1755-1315/220/1/012038. **(Indexed by SCOPUS)**