The comparison of the performance of single-equation models of turbulence kinetic energy and two k-e equation models in hydraulic simulation of dam failure on the mobile bed

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Abstract

The selection of the type of turbulence models has an important impact on the performance of the numerical models for flow simulation in the computational fluid dynamics softwares. This research is conducted to determine the effectiveness of single-equation model of turbulence kinetic energy and two-equation model of K-Epsilon in simulation of positive wave movement caused by dam failure on a mobile bed. The research method included the numerical calculations using Flow-3D software. The reserach results showed that K-Epsilon model is more accurate in predicting the pattern of the flow's free surface. Both models have the same accuracy in calculating the profile of the non-dimensional depth, velocity and acceleration of the advancing front of positive wave. Neither model could predict well the profile of mobile sediment bed. The final conclusion is that K-Epsilon turbulence model has higher efficiency in simulation of flow in dam failure on the mobile bed.

Keywords: turbulence models, turbulence kinetic energy, K-Epsilon, Flow-3D, dam failure

Introduction

Dam failure phenomenon is simply the creation of a fast unsteady flow and the flow appears as the propagation of positive and negative waves respectively to the downstream and upstream of itsformation point (Chow, 1959). The study of this phenomenon is important in the sudden flood forecasting that threatens residential areas and farm land located downstream of the dam and can cause huge life and financial losses (Kocaman, 2015). The first effortsfor solving the problem of dam failure were done by Ritter (1892), Dressler (1952), Whitham (1955) and Stoker (1957). These researchers presented methods, mainly based on the analytical solutions of Saint -Venant shallow water equations.

In general, various researchers used three different approaches, based on experimental modeling, computational methods and a combination of these two methods in solving the problem of dam failure. Experimental approach is mainly carried out in two general forms of dam failures on the dry bed and wet bed. The studies whcih are conducted by the experimental approach include Miller and Chaudhry (1989), Spinewine and Zech (2003), Cristo and Leopardi (2010), as well as Wood and Wang (2015).

Townson and Salihi (1989) usedcharacteristics method forsolving Saint – Venant equationsto model positive wave movement of the dam.

Ancey et al. (2008) studied the dam failure flow on steep slopes by proposingan exact solution for shallow water equations. Ozmen-cagatay and Kocaman (2011)conducted anexperimental - numericalresearch to study the effects of the slope change of the bed and sudden change in channel topography on the dam break flow throughshallow water models and averaged Reynolds equations. Cozzolino et al. (2015) used an experimental - numerical approach for modeling the collision of shock waves caused by the damfailure for the vertical wall located in the end of downstream of the experimental model.

Therefore, it will be seen that among the numerical approaches used in solving dam failure, acomparative study is not conducted on turbulence models, as an importantand effective variable on modeling the flow caused by dam failure on the erodible bed. Thus, this studyemphasized on solving RANS equations, and compared the efficiency of single-equation turbulence kinetic energy models and two- equations kinetic energy–loss ($k-\varepsilon$)insimulation of positive wave motion caused by the dam failure . Flow-3D software version 10.0.1 was used for simulation. The results obtained from the model is compared with the results of the experimental model of Spinewine (2005).

Governing Equations

This study was based on numerical computational modeling using Flow-3D version 10.0.1. The results obtained from the model was verified with results of Spinewine's experimental model (2005). Then, the efficiency of the two turbulent flowmodels of $k-\varepsilon$ and RNG were compared as effective factors on the accuracy of the results of numerical model. The governing relationships on the flow turbulence models are as follows. It should be noted that all relationships of turbulent flow are used in Flow-3D software in combination with FAVOR's area and volume relations.

Single-equation model of turbulent kinetic energy

This model is a single-equation model for theturbulence scales and it is based on the calculation of turbulence kinetic energy K in terms of normal Reynolds stresses.

To calculate K (in non-isotropiccase), the transfer equation is used as follows:

$$\frac{\partial K}{\partial t}+C_1 u\frac{\partial K}{\partial x}+C_2 v\frac{\partial K}{\partial y}+C_3 w\frac{\partial K}{\partial z}=P_t-\frac{CK^{1.5}}{l_m} \qquad (1)$$

$$C_1=\frac{A_x}{\forall_f},\; C_2=\frac{A_y}{\forall_f},\; C_3=\frac{A_z}{\forall_f} \qquad (2)$$

$$P_t=P_{1t}+P_{2t}+\mathrm{diff}_t \qquad (3)$$

$$\varepsilon=\frac{CK^{1.5}}{l_m} \qquad (4)$$

In the above relations, $A, \forall_f, P_t$ and diff_t are respectively FAVOR's area and volume function, turbulence generation and diffusion.

The kinetic energy –turbulence loss model (k-ε):

Two-equations turbulence models are models that use independent transfer equations for length scales of turbulence or turbulence parameters (such as kinetic energy and loss). These models are based on two fundamental assumptions. In a (k-ε) model it is assumed that turbulence viscosity is proportional with the square of turbulent energy divided on turbulence loss (Celik, 1999):

$$\mu t \; \alpha \; \frac{\rho k^2}{\varepsilon}$$

(5)

Turbulence production- loss equations in a stable form are as follows (Mohammadi and Pironneu,1994) :

$$\frac{\partial k}{\partial t} + \vec{U}.\nabla - \nabla.(D_k \nabla_k) + \gamma_k k = F_k$$

(6)

$$\frac{\partial \varepsilon}{\partial t} + \vec{U}.\nabla_\varepsilon - \nabla.(D_\varepsilon \nabla_\varepsilon) + \gamma_\varepsilon \varepsilon = F_\varepsilon$$

(7)

$$D_k = \frac{\nabla_T}{\sigma_k} + \nabla_L, D_\varepsilon = \frac{\nabla_T}{\sigma_\varepsilon} + \nabla_L$$

(8)

(9)

$$\gamma_k = \frac{\varepsilon}{k}, \gamma_\varepsilon = \frac{\varepsilon}{k}$$

$$F_k = \frac{v_t}{2} \,|\, \nabla\vec{U} + \nabla\vec{U}^T \,|^2, F_\varepsilon = \frac{C_1 k}{2} \,|\, \nabla\vec{U} + \nabla\vec{U}^T \,|^2$$

(10)

In 6-10 relationships, U^r is the mean Reynolds, v_t is the turbulence viscosity, K is the turbulence kinetic energy, D_k and D_ε are respectively the production diffusion coefficient and turbulence loss coefficicent, γ_k and γ_ε are respectively production reflection coefficient and turbulence loss reflection coefficient, F_k and F_ε are the spring's terms. Also, C_1=0.126, C_2=1.92, σ_k=1, σ_s=1.3. It should be noted that diffusion and reflection coefficients and spring's terms have non-negative values for physical solutions.

$$\frac{x}{t\sqrt{gH_0}} = X, \frac{x}{H_0} = X^*$$

(11)

$$\frac{H}{H_0} = H^*$$

(12)

$$\frac{t}{\sqrt{\frac{H}{g}}} = t^*$$

(13)

$$\frac{X^*}{{t^*}^2} = a^*, \frac{X^*}{t^*} = U^*$$

(14)

In relationships (11) to (14) x, t, H_0, H, X, H^*, t^*, U^*, a^* are respectively horizental distance, the time spent from the begining of the experiment, the initial depth of water under the valve (in upstream) H is the hight of free surface at t second,non-dimentional variables of horizental distance, non-dimentional variable ofhight of free surface, non-dimentional variable of the progressing velocity of wave front and non-dimentional variable of the progressing acceleration of positive wave front.

Findings

After doing simulations by using turbulence kinetic energy models, and k-ε in Flow-3D software, the results are provided in diagramms, it should be noted that relations (11) to (14) are used in diagramms preparation.

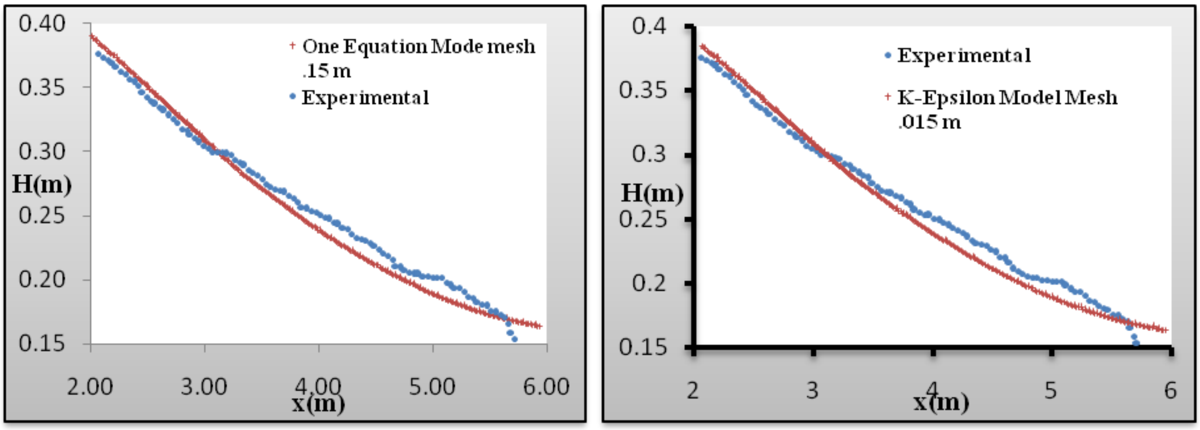

Figure (2)- Profiles of water free surface in turbulence kinetic energy models (rightside) and K-Epsilon(leftside) and the experimental results (t=1.25 s)

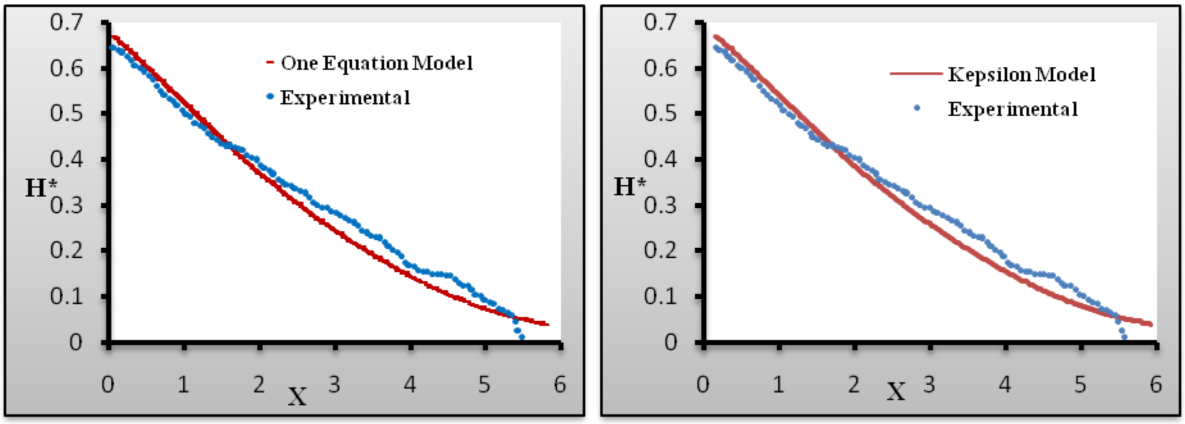

Figure (3)- Non-dimentional profiles of water free surface in turbulence kinetic energy models (rightside) and K -Epsilon(leftside) and the experimental results (t=1.25 s)

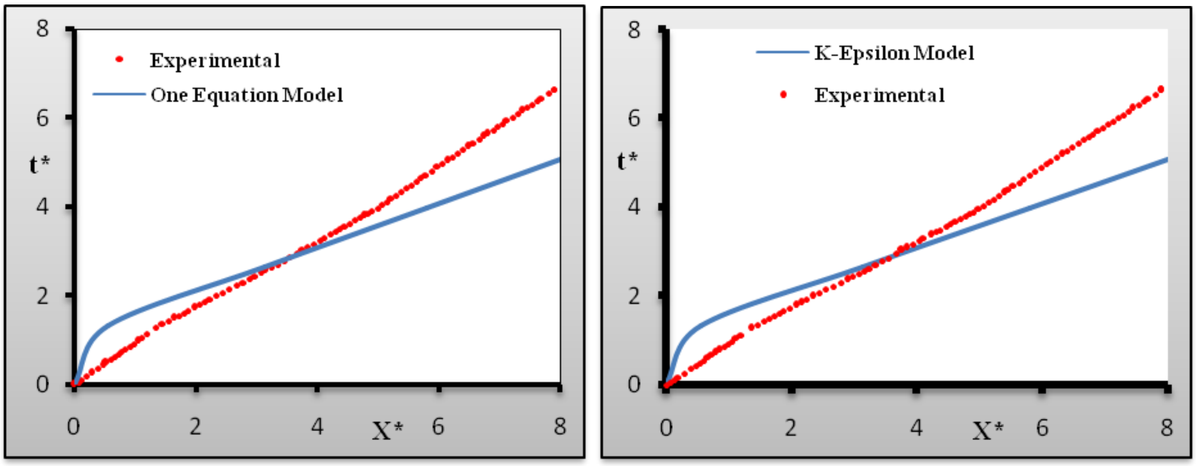

Figure (4)- Non-dimentional profiles of distance- progressing time of positive wave front in turbulence kinetic energy models (rightside) and K -Epsilon(leftside) and the experimental results

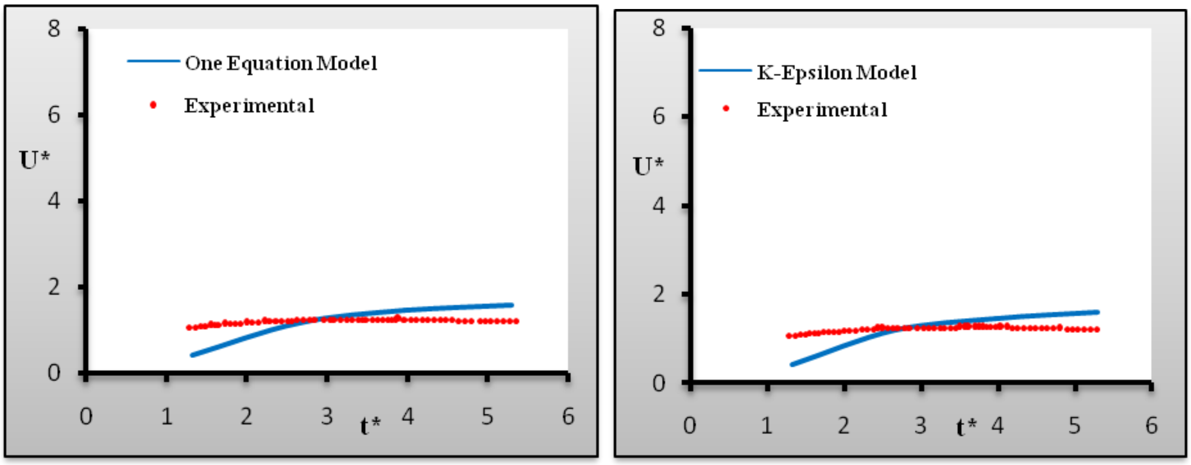

Figure (5)- Non-dimentional profiles of velocity- progressing time of positive wave front in turbulence kinetic energy models (rightside) and K -Epsilon(leftside) and the experimental results

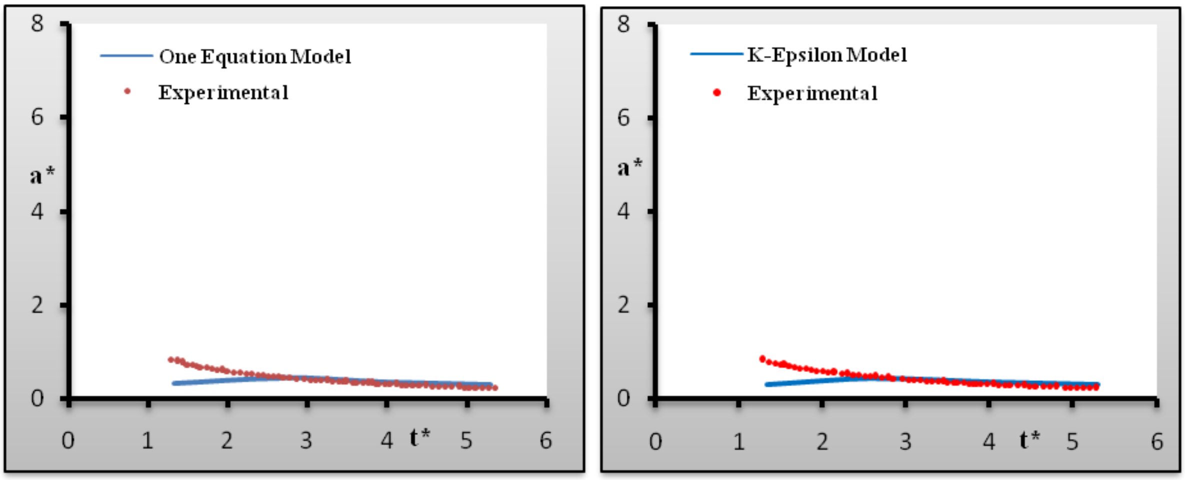

Figure (6)- Non-dimentional profiles of acceleration- progressing time of positive wave front in turbulence kinetic energy models (rightside) and K -Epsilon(leftside) and the experimental results

The accuracy of models in simulations and predictions about the profiles of water free surface is measured based on R^2 criterion and the normal relative error percentage:

$$\varepsilon_L = \sqrt{\frac{\sum_{i=1}^{n}(\varnothing_{\exp_i}-\varnothing_{\mathrm{mod}_i})^2}{\sum_{i=1}^{n}(\varnothing_{\exp_i}{}^2)}} \qquad (15)$$

In equation (13), ε_L is the percentage of normal relative error and $\phi_{ex\ i}$ is the obtained value from the experimental results and $\phi_{mod\ i}$ is the obtained variable from the modeling results.

Table (1)- The value of calculated normal error and R^2 for diagrams (2) to (6) in turbulence kinetic energy models and K -Epsilon

Model Name	Accuracy criteria	Hight of free surface	U^*	a^*
Turbulence kinetic energy	R^2	0.886	---	---
	ε_L	0.036	0.326	0.782
K -Epsilon	R^2	0.906	---	---
	ε_L	0.034	0.326	0.782

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