Computational Analysis of Suspended Particles in the Irrigation Channel

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Abstract. Irrigation channel that is used for bringing water to land in order to make plants grow is one of important thing in tropical country, especially in Indonesia. It has been also a central feature of agriculture for over 5,000 years and is the method in which water is supplied to plants at regular intervals for agriculture. This paper is to analyse the sedimentation process in the irrigation channel in District Deli Serdang, Sumatera Utara Province. The analysis is based on the mixture model in turbulent flow. Computation using Finite Element Method is performed in the domain in two dimensional. The values of dispersed phase density parameter vary from 1100 kg/m³ to 1250 kg/m³. The results have shown that the structure of mixture velocity distribution and the dispersed phase volume fraction.

1. Introduction

North Sumatra Province is one of province in Indonesia that the plantation agriculture is one of the priority economic sectors. The Ministry of Agriculture of the Republic of Indonesia has published statistical data, i.e. land area of rice in 2015 reached 781.769Ha (5.54% of the rice land area of the entire Indonesian) with a growth rate last reached 8.98%. Especially, the production of rice in 2015 from the province of North Sumatra reached 4.044.829Ton (5.37% of rice production throughout Indonesia) with the last growth reached 11.40% [1]. This rate of growth of land area is still high, even though it is still low compared to several provinces in Java.

Researches on sediment transport are mostly considered to derive the prediction equations for solid discharge and to analyze the grain kinematics and dynamics [2]. The smooth bed configuration can give insight into how the turbulent flow affects the sediment motion [3]. On the other hand, an experimental configuration filters out the interaction of moving particles with the bed roughness and with other moving grains [4]. Building settling basin is traditionally built based on retention time [5]. The evolutions of flow pattern and sediment transportation at a 90° open-channel confluence with different discharge ratios of the tributary flow to the total flow have been studied experimentally by Liu et. al [6].

Analysis using computation on a physical phenomenon that occur in a real situation can be performed using computer-aided technology considering some governing equation and boundary conditions. The process of sedimentation in a building settling basin can be analyzed to obtain the optimal parameters, so it can produce more efficient performance. The application of characteristics of water flow and sediment transport based simulations to predict sediment transport and water in the river system has been studied by Sil, B.S. and Choudhury [7]. Some authors have also derived the profile shape model
of the river, and sedimentation models on a tube and have also conducted experimental studies some basic changes in a channel and formulate conditions channel geometry and characterize the effects of geometry and flow [8, 9].

A laboratory study of open-channel confluences using a 3D has been performed by Bradbrook et al. Some elliptic solution of the Reynolds-averaged Navier-Stokes equations have been analyzed, including a method for approximating the effects of water surface elevation patterns [10]. There are some other researchers studied the flow pattern and sediment transportation at channel confluence with respect to the momentum equations, energy equations, and potential theory [11, 12].

2. Sedimentation Phenomenon

The derivation of the phenomenological theory for settling of sedimentation with compression was conducted by Concha and Bustos [13]. The hydrodynamic can be modeled as a Reynolds Averaged Navier-Stokes (RANS) equations and on the standard k-ε model for turbulence processes. The sediment transport can be derived as a mass balance equations for the re-suspended sediment [14].

A suspension is a mixture of solid particles and a liquid. In this theory, a suspension was modeled as a mixture of two superimposed continuous media. The dynamics of a suspension can be modelled by a momentum transport equation for the mixture, a continuity equation, and a transport equation for the solid phase volume fraction. The Mixture Model, Laminar Flow interface automatically sets up these equations. It uses the following equation to model the momentum transport:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p - \nabla \cdot (\mu + \mu_t) \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) + \nabla \cdot \left[ \rho_c (1 - c_s) \mathbf{u}_{slip} \mathbf{u}_{slip} \right] + \rho g$$

(1)

where \( \mathbf{u} \) is the mass averaged mixture velocity (m/s), \( p \) denotes the pressure (Pa), \( g \) refers to the acceleration of gravity (m/s²), \( c_s \) is the dimensionless particle mass fraction, and \( \mathbf{u}_{slip} \) gives the relative velocity between the solid and the liquid phases (m/s).

3. Finite element analysis for Sedimentation

Sediment deposition problems on the channel need to be handled appropriately. The deposition of sediments in these channels will cause problems in the development of agricultural production and the cultivation of paddy fields. Based on the above ideas, it will be evaluated the building settling basin. The analysis in this paper considers the 2D of the channel. To analyze the sedimentation process, it is considered the equation of momentum transport from the equations (1) to give the dynamic of the problem. So, the following governing equations are considered to the problem of mixture model in turbulent flow.

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot \left[ -p I + \left( \mu + \rho \frac{\partial u}{\partial t} \right) \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) \right] - \nabla \cdot \left[ \rho_c (1 - c_s) \mathbf{u}_{slip} \mathbf{u}_{slip} \right] + \rho g + \mathbf{F}$$

(2)

$$\left( \rho_c - \rho_d \right) \left\{ \nabla \cdot \left[ \rho \frac{\partial \phi_d (1 - c_d)}{\partial t} \mathbf{u}_{slip} - D_{md} \nabla \phi_d \right] + \frac{m_{dc}}{\rho_c} \right\} + \rho_c (\nabla \cdot \mathbf{u}) = 0, \quad \rho \frac{\partial \phi_d}{\partial t} + \nabla \cdot \mathbf{N} \phi_d = -\frac{m_{dc}}{\rho_c}$$

(3)

$$\phi_d = p \mathbf{hid}, \quad N_{\phi_d} = \phi_d \mathbf{u}_d, \quad \mathbf{u}_d = \mathbf{u} + \phi_d (1 - c_d) \mathbf{u}_{slip} - \frac{D_{md}}{\phi_d} \nabla \phi_d$$

(4)

$$\rho = \rho_c + \phi_d \rho_d, \quad c_s = \phi_d \rho_d, \quad D_{md} = \frac{\mu \rho}{\rho \sigma T}$$

(5)

The boundary conditions are considered with respect to the real condition of the model, that are wall, slip wall, inlet, and outlet.
The 2D geometric model and the boundary conditions are designed as depicted in Figure 1 (a). The water inlet is applied at the left side, and the water outlet is applied at the right side and the right bottom side. Wall slip is applied at top side, and the rest are set as the wall. By using Finite Element Method, the mesh is generated using triangle elements as depicted in Figure 1 (b). An initial-boundary value problem was derived by introducing constitutive assumption, simplifying the balance, and restricting to one space dimension. The problem was of the form of a second order partial differential equation for volumetric solid concentration. The mixed type nature corresponds to the interface between the compression zone, where the solid effective stress varies, and the hindered settling zone.

Table 1. Specification of the material properties

| No | Parameter                  | Symbol | Value   | Unit     |
|----|----------------------------|--------|---------|----------|
| 1  | Continuous phase density   | $\rho_c$ | 1000    | kg/m³    |
| 2  | Continuous phase viscosity | $\mu_c$ | 0.001   | Pa·s     |
| 3  | Dispersed phase density    | $\rho_d$ | 1100-1300 | kg/m³ |
| 4  | Dispersed phase particle diameter | $D_d$ | 2E-4    | m        |

The parameters used in the computation are considered as a description for the material properties of water and the averaged diameter of particle dispersed in water as described in Table 1. On the other hand, some values are given in initial values of the computation with deal to the condition in the channel as listed in the Table 2.

Table 2. Some variables that used in the computation

| No | Variables                  | Symbol | Value                   | Unit    |
|----|----------------------------|--------|-------------------------|---------|
| 1  | Inlet velocity             | $v_{in}$ | 1.25*step function     | m/s     |
| 2  | Outlet velocity            | $v_{out}$ | 1.25*step function     | m/s     |
| 3  | Inlet dispersed phase volume fraction | $\phi_{d_{in}}$ | 0.003                | -       |
| 4  | Dispersed phase mass-out flux | $q_{d_{out}}$ | $2\pi\phi_{d_{in}}$ | kg/(m·s) |

4. Results and Discussions

This section will show the distribution of velocity and volume fraction of the dispersed phase in the channel in some units of time. Figure 2 shows the distribution of velocity in the channel time by time, i.e. from 0.0s to 0.4s. The computational observation is performed to the distribution of velocity. There are some uniformly velocity that can cause a turbulence in the channel. The distribution of the mixture...
velocity varies time by time. Figure 2 shows also that the maximum velocity occurs at the surface of the channel. The initial velocity in the computation was set to be 0 m/s at \( t = 0 \). Table 3 shows the maximum mixture velocity in the channel at some time of computation.

**Table 3. The maximum mixture velocity in the channel**

| Time (sec) | \( \rho_d = 1100 \text{ kg/m}^3 \) | \( \rho_d = 1200 \text{ kg/m}^3 \) | \( \rho_d = 1300 \text{ kg/m}^3 \) |
|-----------|----------------------------------|----------------------------------|----------------------------------|
| 0.00      | 0.0000                           | 0.0000                           | 0.0000                           |
| 0.10      | 1.1983 \times 10^{-5}           | 2.7546 \times 10^{-5}           | 1.5645 \times 10^{-4}           |
| 0.20      | 4.4709 \times 10^{-5}           | 1.1765 \times 10^{-4}           | 5.0363 \times 10^{-4}           |
| 0.30      | 1.0702 \times 10^{-4}           | 3.1265 \times 10^{-4}           | 9.9879 \times 10^{-4}           |
| 0.40      | 1.4391 \times 10^{-4}           | 7.8201 \times 10^{-4}           | 1.8859 \times 10^{-3}           |

Figure 3 shows the graph of maximum velocity versus time with respect to the dispersed phase densities. Higher dispersed phase density, higher the maximum velocity. Compared with the Figure 2, it appears that higher in speed changes causes the velocity distribution is not consistent. This can lead to turbulence in that area. The streamlines of the mixture dispersed phase volume fraction at several times of computation. From the Figure 2, the distribution of volume fraction is suitable with the velocity field. Opposing effects of gravity settling and turbulence-induced particle dispersion produce volume-fraction gradients in the interior. The magnitude of the mixture strain rate (and hence the turbulence production) decreases with the distance from the inlet side.

![Figure 2](image-url)
Figure 3. Volume fraction distribution of the dispersed phase

The streamlines show the differences of mixture fraction in some areas. At time 0.0, the form of the streamline is relatively uniform. The streamlines change from time to time. In times of 0.1 s to 0.4 s, the solid fall to channel bed with respect to the form of the streamlines. The different values of dispersed phase density affect the structure of streamline of the mixture fraction. The value 1100 kg/m$^3$ of dispersed phase density is more suitable compared with the other higher values.

Figure 4. Minimum and maximum volume fraction versus time

The minimum and maximum of mixture fraction change with respect to time computation. From the Figure 4, the minimum mixture fractions decrease, with respect to dispersed phase densities 1100 kg/m$^3$, 1200 kg/m$^3$ and 1300 kg/m$^3$, from 2.9793 x 10$^{-3}$ to 7.802 x 10$^{-4}$, from 2.9537 x 10$^{-3}$ to 0, and from 2.9235 x 10$^{-3}$ to 0, respectively. On the other hand, the maximum mixture fraction tends up, from 3.0185 x 10$^{-3}$ to 6.6335 x 10$^{-3}$, from 3.0327 x 10$^{-3}$ to 1.0101 x 10$^{-2}$, and from 3.0443 x 10$^{-3}$ to 1.26 x 10$^{-2}$, respectively. It means that the mixture fraction in the channel firstly almost uniform, and the range of mixture fraction tends to big. The higher value of dispersed phase density, then faster the particles tend down. Physically, it means that in some areas of the channel, the solid in mixture fall to ground of the channel.

5. Conclusions

A 2D numerical computation based on momentum transport equation for the mixture is presented to search the relationship between the sediment movement, and the pattern of volume fraction of the dispersed phase in the channel. From a computational point of view, results have shown the importance
streamlines of the mixture velocity and the dispersed phase volume fraction. From a physical point of view, results highlighted the contour of the volume fraction according to the water flow with deal to the inlet and outlet position.

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