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Numerical Analysis Study of Sarawak Barrage River Bed Erosion and Scouring by Using Smooth Particle Hydrodynamic (SPH)

To cite this article: M R R M A Zainol *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **267** 012010

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Numerical Analysis Study of Sarawak Barrage River Bed Erosion and Scouring by Using Smooth Particle Hydrodynamic (SPH)

M R R M A Zainol^{1,4}, M A Kamaruddin^{2,4}, M H Zawawi^{3,4}, and K A Wahab¹

¹School of Civil Engineering, Universiti Sains Malaysia, Penang, Malaysia

²School of Industrial Technology, Universiti Sains Malaysia, Penang, Malaysia

³College of Engineering, Universiti Tenaga Nasional, Bandar Baru Bangi, Malaysia

⁴Centre of Excellence Geopolymer and Green Technology (CEGeoGTech), Universiti Malaysia Perlis, Perlis, Malaysia

E-mail: ceremy@usm.my

Abstract. Smooth Particle Hydrodynamic is the three-dimensional (3D) model. In this research work, three cases and one validation have been simulate using DualSPHysics. Study area of this research work was at Sarawak Barrage. The cases have different water level at the downstream. This study actually to simulate riverbed erosion and scouring properties by using multi-phases cases which use sand as sediment and water. The velocity and the scouring profile have been recorded as the result and shown in the result chapter. The result of the validation is acceptable where the scouring profile and the velocity were slightly different between laboratory experiment and simulation. Hence, it can be concluded that the simulation by using SPH can be used as the alternative to simulate the real cases.

1. Introduction

Water flow has their own energy in the river. By that energy, the river changes their physical characteristics such as the shape which can be wider, deeper and longer. The material that has been transported from places to another places is caused by erosion of the river bed and river banks. Focusing on the river bed erosion, the changes of the river bed level can happen in both upstream and downstream of the river through the different of the head pressure. According to Chu (2014), river channel-bed erosion and deposition not only affects river sediment flux to the sea but also influences the river regime and associated management practices like in-channel navigation, flood control, and levee maintenance. These have been longstanding issues for many large rivers around the world, such as the Mississippi, the Amazon, the Yellow, the Yangtze and the Pearl.

¹ To whom any correspondence should be addressed.



Generally, at the barrage, the level of water at upstream is higher than the level of water at downstream. The greatest part of river bed to be eroded is at downstream of the river. When the barrage is opened, the highest head pressure of

water will flow to the lower head pressure and scouring or river bed erosion will occurred at those location. Based on Stefan et al. (2016) the residual flow energy will produce scour in an alluvial riverbed if no mitigation structure (such as a dissipation basin) is installed downstream of a grade-control structure. In the absence of a technical dissipation structure or a downstream apron, scour can occur in a loose riverbed downstream. Bhuiyan et al. (2007) investigated the effect of a W-weir (without upstream or downstream apron) on the downstream sediment transport processes, focusing on the scour-hole formation. The maximum scour depth was observed a short distance downstream of the weir, independent of the boundary conditions.

Therefore, by undergo the numerical simulation method the river bed erosion and scouring can be easily identified. The location of the phenomenon and other data can be obtained by using Smooth Particle Hydrodynamics (SPH). SPH could play a very useful role in determine the condition of the river bed at the barrage. The gathered information could lead to a new discovery and helps to improve the river condition.

1.1. Study area

This study actually is about the river bed erosion at downstream of the Sarawak Barrage which is over the Sarawak River connected to the sea. Sarawak River mouth is located near to the Kuching city. There is a barrage that also known as Kuching Barrage which has been constructed and completed in October 1997 which is located at the mouth of the Sarawak River as ‘Figure 1’. The operation of the barrage started on January 1998 and the barrage has been built for the flood mitigation project. The barrage also act as a dam by providing fresh water for the water treatment plant. It also prevent or minimize saline intrusion to the water treatment plant.

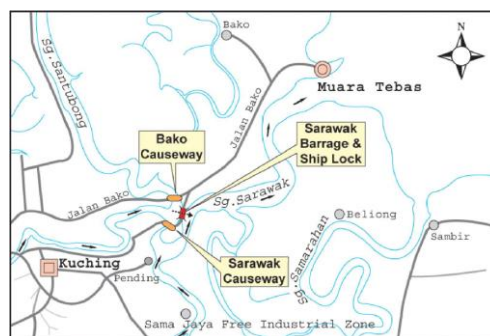


Figure 1. Sarawak River

The barrage has 5 movable gates that consist of radial and tidal gates and 1 ship lock with 2 radial gate which all the gates operated hydraulically. The barrage gates are 25 meters in width of each and a ship lock alongside of the barrage. The barrage also has a flyover on top of it with two causeways across Sarawak River at Pending and Santubong River at Bako

2. Numerical Method

For this study, the case that will be chosen in the software is Multi-phase case where it's liquid-sediment model solver.

The whole system is represented by a finite number of particles that carry individual mass and occupy individual space. Particle approximation aims to discretize the kernel approximation within the support domain. Fig. 2.1 provides a clearer picture on how the kernel function can be used to estimate a field variable of particle i within a radius h .

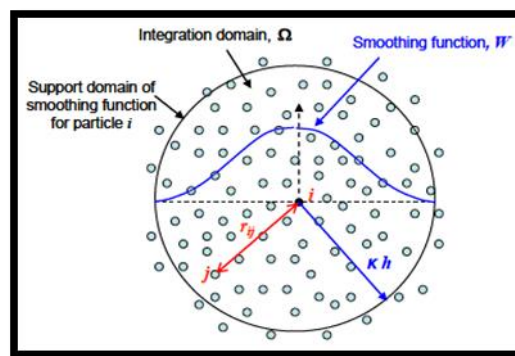


Figure 2. Support domain with a radius of kh and smoothing kernel function, W for particle i

The mass of the particles m_j is related to the finite volume of the particle, ΔV_j and its density of ρ_j , as follows:

$$m_j = \Delta V_j \rho_j \tag{1}$$

The integral form of the interpolation can be discretized as the summation of N neighboring particles (number of particles that interact with particle i and can be written as:

$$f(\mathbf{x}) = \int_{\Omega} f(\mathbf{x}') W(\mathbf{x} - \mathbf{x}') d\mathbf{x}' \cong \sum_{j=1}^N \frac{m_j}{\rho_j} f(\mathbf{x}_j) W(\mathbf{x} - \mathbf{x}_j, h) \tag{2}$$

It is noted that infinitesimal volume $d\mathbf{x}'$ is replaced by the finite volume of the particle ΔV_j . The final discretized form for the particle approximation function of particle i is:

$$\langle f(\mathbf{x}_i) \rangle = \sum_{j=1}^N \frac{m_j}{\rho_j} f(\mathbf{x}_j) \cdot W_{ij} \tag{3}$$

where

$$W_{ij} = W(\mathbf{x}_i - \mathbf{x}_j, h) \tag{4}$$

Thus, the value of a variable at particle i is estimated as the sum of the values it assumes on the neighbouring points within the support domain weighted by the smoothing kernel function.

SPH involves the computation of discretized fluid into a set of particles, each particle is referred to a nodal point where physical quantities are computed as an interpolation of the values of the nearest particles. The integral approximation of any function $A(\vec{r})$ is

$$A(\vec{r}) = \int_{\Omega} A(\vec{r}')W(\vec{r} - \vec{r}', h)dr' \tag{5}$$

where h is the smoothing length and $W(r - r', h)$ is the weighting function or smoothing kernel.

The function $A(\vec{r})$ can be expressed in the discretized form and the approximation of the function at particle a is given by:

$$A(\vec{r}) = \sum_b m_b \frac{A_b}{\rho_b} W_{ab} \tag{6}$$

where m_b and ρ_b being the mass and density associated to the neighboring particle b , respectively. Besides, the term $W_{ab} = W(\vec{r}_a - \vec{r}_b, h)$ describes the weight function.

SPHysics provides four different kind of kernel definitions. For this particular research, the cubic spline kernel is selected and showed as follows:

$$W(r, h) = \alpha_D \begin{cases} 1 - \frac{3}{2}q^2 + \frac{3}{4}q^3 & 0 \leq q \leq 1 \\ \frac{1}{4}(2 - q)^3 & 1 \leq q \leq 2 \\ 0 & q \geq 2 \end{cases} \tag{7}$$

where $\alpha_D = 1/(\pi h^3)$ in three-dimensional flow domain.

The momentum conservation equation in a continuum Eulerian field is shown as follows:

$$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\vec{\nabla}P + \vec{g} + \vec{\Theta} \tag{8}$$

where $\vec{\Theta}$ denotes the diffusion term.

The momentum equation in SPH method can be described by different approaches based on various existing formulations of the diffusive terms. The momentum equation is implemented to determine the acceleration of a particle a as a result of the particle interaction with its neighbours, particles b :

$$\frac{d\vec{v}_a}{dt} = -\sum_b m_b \left(\frac{P_b}{\rho_b^2} + \frac{P_a}{\rho_a^2} \Pi_{ab} \right) \nabla_a W_{ab} + \vec{g} \tag{9}$$

Such that v being the velocity, P is the pressure, ρ is the density, m is the mass of particle, $\vec{g} = (0, 0, -9.81) \text{ m/s}^2$ is the three-dimensional gravitational acceleration vector and W_{ab} denotes the kernel function that dependent on the distance between particles a and b .

The mass of each particle is set to be constant, so that changes in fluid density are computed by solving the conservation of mass or continuity in SPH which is given as:

$$\frac{d\rho_a}{dt} = \sum_b m_b \vec{v}_{ab} \nabla_a W_{ab} \tag{10}$$

Pressure is calculated starting from density using Tait's equation of state as shown below:

$$P = B \left[\left(\frac{\rho}{\rho_0} \right)^\gamma - 1 \right] \tag{11}$$

where the constants $B = c_0^2 \rho_0 / \gamma$ and $\gamma = 7$, for such that the reference density, $\rho_0 = 1000 \text{ kg/m}^3$ and the corresponding speed of sound at this particular reference density,

$$c_0 = c(\rho = \rho_0) = \sqrt{(\partial P / \partial \rho)}|_{\rho_0} \tag{12}$$

Particles are moved using the SPH variant. SPH ensures each particle movement is consistent with the average velocity of its neighboring particles on particle distribution. In other words, the purpose of SPH is to make fluid particle flows together with its neighboring fluid particles to make it more localized and stable.

3. Methodology

3.1. Data collection

Data collection are very important to obtain information in this study. Through the study site area, field data will be used in the SPH as the raw data. The data that gathered from site such as density of water, density of bed material, cohesion value of the bed material and also water depth will be as input to the program. Besides that, the details of the particle sizes and viscosity also important because it can give an effect to the movement of sediment particles in the simulation. All the parameters must have to be as an input in the SPH software.

Not only that, the characteristics and trend of the barrage also important such as the geometry. The geometry data are obtained through the drawing of Sarawak Barrage will be used for modelling during pre-processing process. To develop the model in the SPH program, the geometry of the barrage has been drawn in the SolidWork program in three-dimensional (3D) and then convert it to the STL file. Figure 3.7 shows the 3D drawing of Sarawak Barrage in scale by using SolidWork. All the geometry of the Sarawak Barrage need to be extracted and redraw back in AutoCADD every detail section to scale 1 to 25 before redraw back in SolidWork software as shown in Figure 3. Type of gates, size of the barrage, and shape of the barrage structure needs to draw clearly in the software. The dimension and criteria of the barrage should be proper managed.

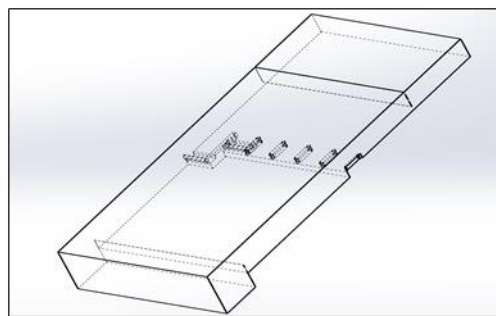


Figure 3. Sarawak Barrage model in 3D SolidWorks

3.2. Numerical analysis

The initial configuration of the simulation such as movement description and parameters are define in the GenCase file name which consider as Pre-processing process. All the input information contains in the XML format; Case_Def.xml. After running GenCase, two output files are created which are Case.xml and Case.bi4. All the parameters of the system configuration such as smoothing length, density, gravity, number of particles and moving boundaries are contained in Case.xml file. While for the Case.bi4 file contains the initial state of the particles is in BINX4(.bi4) format. Paraview software is used to visualize the particle geometries that create with GenCase (Case_All.vtk, Case_Bound.vtk and Case_Fluid.vtk).

Processing-process is where the case that has been create in pre-processing in the process and the SPH simulation performs via named DualSPHysics. All the input file XML file (Case.xml) and binary file (Case.bi4) that has been setup the parameters run through DualSPHysics code. The output files after run the software consist of binary format file that include the particle information of the simulation. This is where analysis of the numerical simulation in progress.

Post-processing process where the output of binary files of DualSPHysics will convert into different format by using PartVTK code that is can allow the output to be visualized and analysed. The results of the simulation can be viewed and analyse by using Paraview from the output files. Post processing is where the simulation and the result obtained from the numerical analysis DualSPHysics.

3.3. Validation

To study the effectiveness and the accuracy of the numerical simulation analysis DualSPHysics, the validation by experiment using the laboratory equipment should be made. For validation of the software, the experiment of the water flow through the sediment is by using the flume.

The experiment starting with by placing sand in the flumes as the sediment. The distance of the sand between the borders was set as 0.5m and the borders size is 0.05m x 0.05m x 0.3m each. The sediment height was set the same as the borders height which is 0.05m. Figure 4 show that the sediment setup.



Figure 4. Sediment placement (sand)

Then the experiment was running within case $8.222 \times 10^{-3} \text{m}^3/\text{s}$ flow rate by setting the valve for that flow rate. Then by using velocity meter, the velocity of the water flow is measure within five points as shown in the Figure 5. After that, measure the sediment high at several point within the depth of changing.

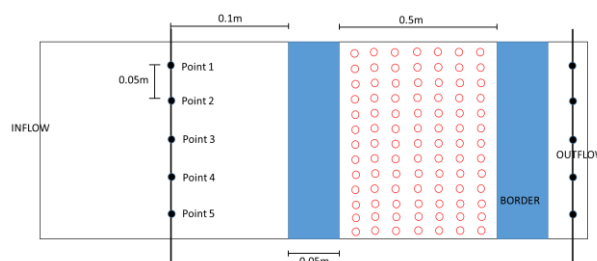


Figure 5. Plan view layout of flume with point measure velocity

4. Results and Discussion

4.1. Case 1

The water level for upstream for this case is 0.34m which has been scale from the real water depth 8.5m. While the water level for downstream has been set for 0.32m which has difference only 0.02m. To measure the scouring profile in the simulation, the distance of the location is 0.5m from the barrage pier. The scouring depth and changing is measured through the side view of the barrage and the point of location has been slice at the middle of each Gate 1 (A-A), Gate 2 (B-B), Gate 3 (C-C), and Gate 4 (D-D) as shown in Figure 6. The red colour of particle denotes sediment particle while the other denotes as liquid particle. Figure 7 shows the cut section of the sediment for the all gate and shape of the scouring profile.

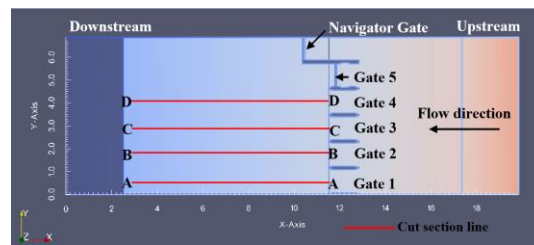


Figure 6. Plan view of barrage simulation

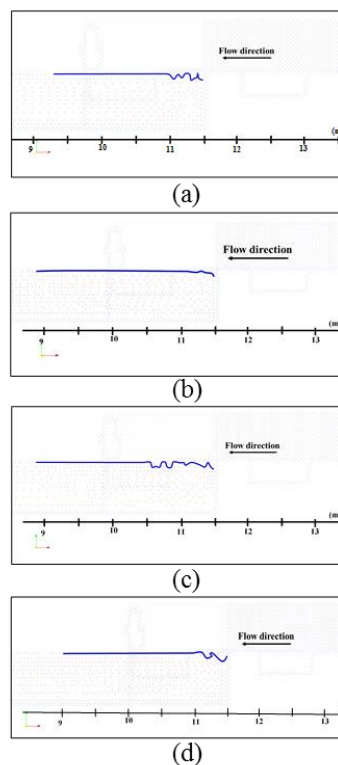


Figure 7. (a) Gate 1 (b) Gate 2 (c) Gate 3 (d) Gate 4 scouring profile

The sediment particle coordinates has been plotted in the Figure 8 with different gate. From that plot, we can see the scouring profile and the scouring depth very clearly. The maximum depth of the

scouring is at the Gate 4 which approximately 0.09m. But for the other gate, the maximum scouring depth approximately 0.06m. Even though the scouring depth not very high, it still dangerous to the hydraulic structure because the scouring happen nearly to the apron of the Sarawak Barrage gate.

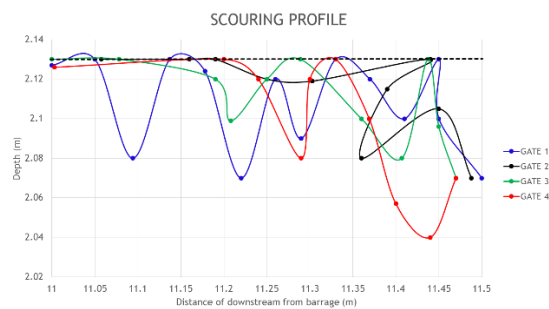


Figure 8. Scouring depth profile

The scouring pattern at the gates approximately similar. The scouring happen when the water passes the barrage apron and hit the water also sediment with different velocity value on each gate. The sediment was eroded by the water within 0.06m for the first phase after barrage apron and the scouring happened. All the sediment particle that has been eroded change their places from origin and moving to the direction of downstream. Figure 9 shows the distribution contour that has been cut to the section and view from the front for the four gate.

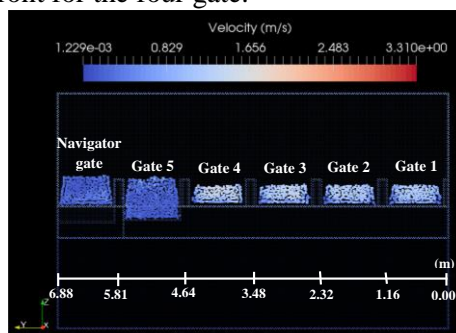


Figure 9. Cut section velocity contour

For the cut section of the Case 1, mostly the Gate 1, 2, 3 and 4 has the approximately same the average velocity which is 1.22m/s at the top. It is the highest velocity on that section. While at the middle of the liquid particle velocity is 1.1m/s which little bit less than the top velocity. But for the bottom velocity of the section is 0.6m/s. The deformation of the sediment particle was influenced by the velocity of the liquid. The flow of the top surfaces give the big impact of the stress for sediment particle which causes of the scouring and erosion.

4.2. Case 2

The water level at the downstream of the Sarawak Barrage is 0.26m from the bed level. While the water level at the upstream is same as first case 0.34m. The pattern of the scouring and the deformation of the river bed that has been eroded as shown in Figure 10. For this cases, the scouring depth less than the first case and more than the third case. The pattern of the scouring profiles are not very drastically eroded within the distance. The scouring profile almost the same for each gate.

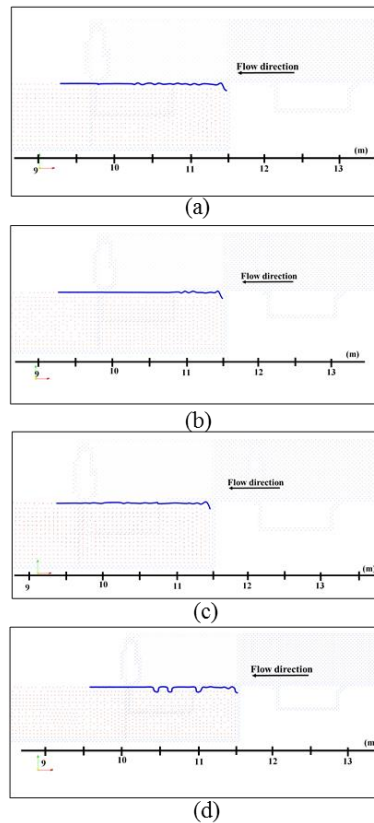


Figure 10. (a) Gate 1 (b) Gate 2 (c) Gate 3 (d) Gate 4 scouring profile

In Figure 11 the scouring profile of each gate shows that pattern and the scouring depth of the sediment within 0.5m from downstream barrage apron has been plotted by using the X-coordinates and the Z-coordinates. The result shown that the maximum scouring depth is approximately 0.05m and the value is same for each gate. This mean the velocity of the water flow have the same value during flow through the barrage.

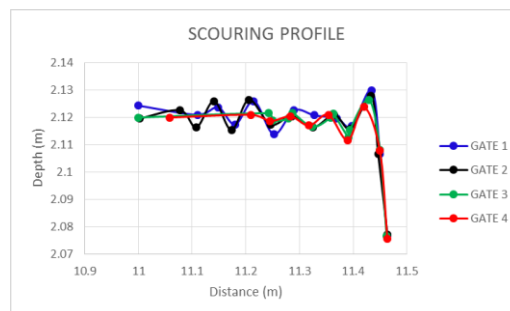


Figure 11. Scouring depth profile

For the case of the 0.26m water level at the downstream, the velocity of the gate is different on each gates. The highest velocity value at the Gate 4 while the lowest is at Gate 1 with 0.73m/s and 0.48m/s, respectively. Figure 12 shows the velocity contour from the cut section of the barrage.

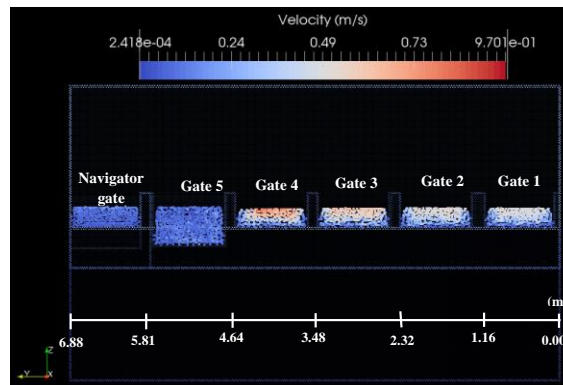


Figure 12. Cut section velocity contour

4.3. Case 3

For Case 3, the water level at downstream is 0.22m while at the upstream is still same. After 5 second simulation, the result has been taken same as the previous case location. Only the water level at downstream has a different. The sediment particle change can be seen clearly as shown in Figure 13. From the sediment particle view from the side of the barrage, the profile of the scouring can be seen clearly.

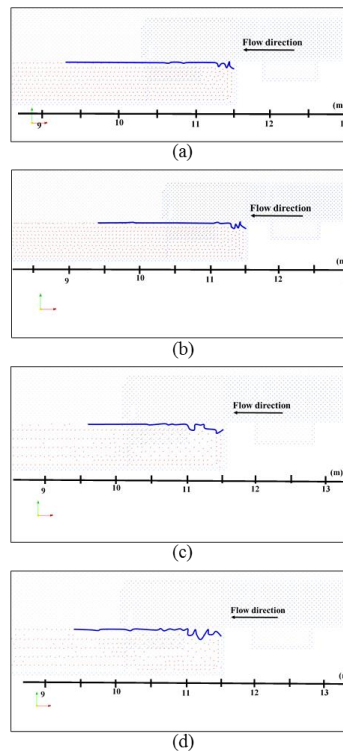


Figure 13. (a) Gate 1 (b) Gate 2 (c) Gate 3 (d) Gate 4 scouring profile

The scouring depth and the scouring profile plotted in Figure 3.9. The result shown that the highest depth of the scouring is in front Gate 3 with the depth approximately 0.13m. The scouring depth for this case is critical where all sediment particle has been eroded very significantly. The pattern of the scouring also can be seen clearly in Figure 14. The pattern of the scour profile for this case has large deformation from the original profile as compared to the other cases.

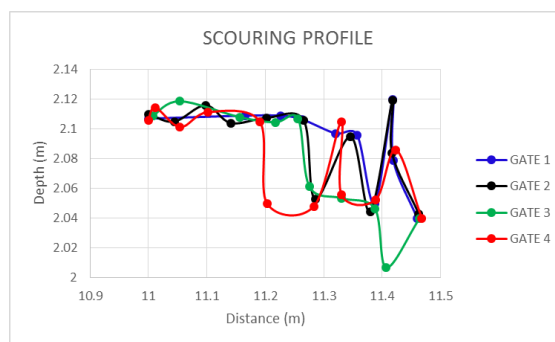


Figure 14. Scouring depth profile

The highest average velocity of this case at the top of the Gate 4 which is 0.9m/s. The water level for this simulation cases is the lowest which is 0.22m at the downstream of the barrage. Because of that water is much lower than the water level upstream, the water particle is moving very fast due to the less of stress to interact with the other particle. It is also due the head different of the water level that affect to the water energy. The contour of the velocity as shown in Figure 15.

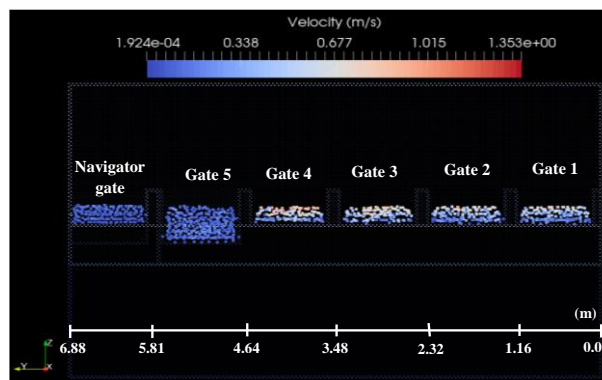


Figure 15. Cut section velocity contour

The result obtains also show the same phenomenon of the velocity where at the top level is the highest, while the bottom level velocity is the lowest and the middle velocity is in intermediate between top and bottom. The lowest velocity is at the bottom of Gate 1. But the value does not differ much with the bottom Gate 2. While for the Gate 3 and 4 at the bottom, the average velocity is same. That's mean the water flow with the constant rate and at normal flow. The contour of the velocity on each gate can be seen clearly in Figure 15.

4.4. Validation

To make sure the results obtained from the simulation program were accurate, the validation of the software need to be investigated between the experiment and the numerical analysis simulation. The validation has been made based on the velocity of the water flow in the experiment and the numerical simulation. By measuring the velocity in the experiment at the middle of water depth by using Nixon Streamflo velocity meter, Table 1 shows the result obtained from the experiment.

Table 1. Velocity obtained by Nixon Streamflo meter

Point	1	2	3	4	5
Velocity (m/s)	0.219	0.223	0.225	0.28	0.221

The average velocity in the experiment is 0.223m/s. From the simulation by using SPH, the point to measure the velocity are same as the laboratory experiment. But the raw velocity from SPH is in the velocity vector. After change the vector to the magnitude velocity, the value get the real velocity. Table 2 shows the result obtained from the simulation.

Table 2. Velocity obtained by numerical simulation

Point	1	2	3	4	5
Velocity (m/s)	0.23	0.26	0.27	0.3	0.22

As can be seen in Figure 16 Coefficient of Determination (R²), comparison between observation and simulation has been made. The R² value between the observation in the laboratory experiment with simulation is approximately 0.9 which results the simulation value are acceptable. That is mean the difference of the velocity are still in the range of acceptable.

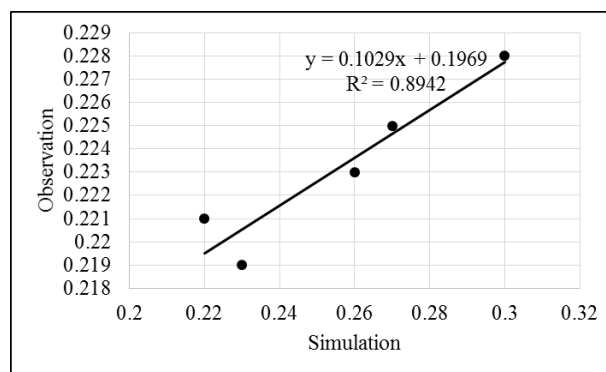


Figure 16. R² relationship between observation and simulation

The shape of the scouring or degradation of the sediment particle can be used to validate the result between the experiment and simulation. The result obtains from the laboratory experiment by measuring the depth of the scouring as shown in Figure. 17 and the depth of the scouring for the simulation in Figure 18. Figure 19 show scouring shape pattern.

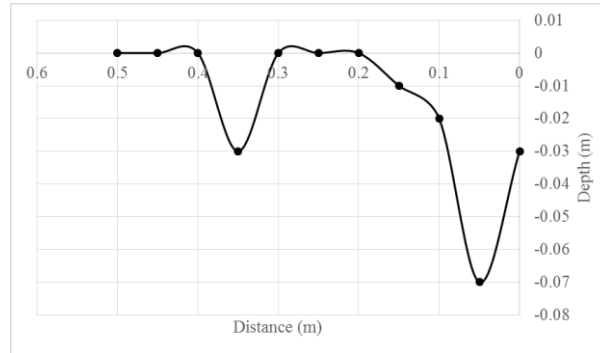


Figure 17. Experimental scouring profile

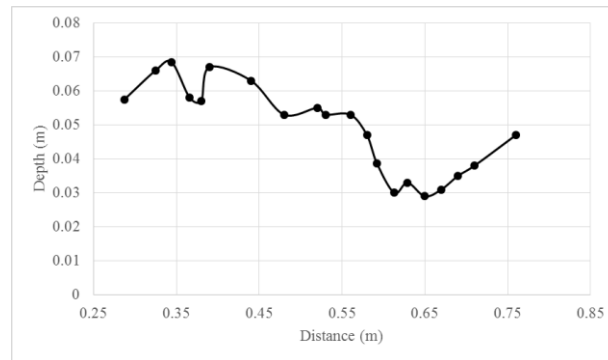
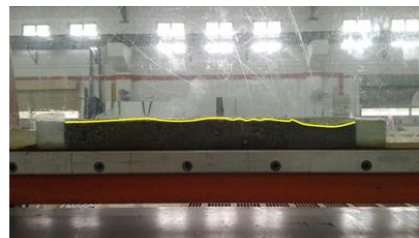
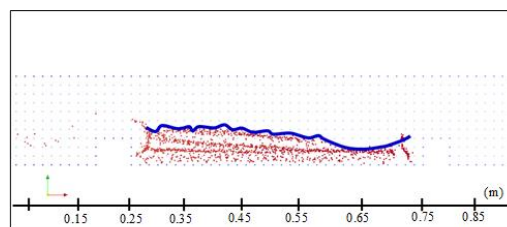


Figure 18. Simulation scouring profile



(a)



(b)

Figure 19. (a) Experimental (b) simulation scouring shape pattern

As a result, the pattern of the scouring profile explicit similar pattern between the laboratory experiment and numerical analysis simulation. The maximum scouring depth of the experiment is

0.07m and for the simulation is 0.03m. From the result as shown, the profile of the scouring by SPH simulation is acceptable and can be used to simulate the real cases.

5. Conclusion

This research described the usefulness of the DualSPHysics (SPH) three-dimensional (3D) to solving the hydraulic problems by using numerical analysis simulation of the Sarawak Barrage. The simulation of the cases is to get the velocity of the flow and the scouring profiles. Three cases have been implemented in this research study of the Sarawak Barrage river bed erosion which is Case 1, Case 2 and Case 3. The different water level at downstream of the barrage between Case 1, Case 2 and Case 3 were 0.32m, 0.26m and 0.22m respectively. While the upstream water level of the barrage for the three cases remain same as 0.34m. To prove the result from the simulation, the validation of one case has conducted to ensure the accuracy of the result and also acceptable.

The validation process was conducted by comparing the velocity and scouring profile between the laboratory experiment and the numerical analysis simulation SPH. As the result, numerical analysis of SPH program can be used to simulate the real cases because it was proven by the validation in this research. However, high performance computer need to be used for running the real cases because the software denotes the fluid as the particle. As a final conclusion, the objectives of the study have been achieved.

The result of the simulation has been validated with laboratory experiment and the data obtained was accepted. The result obtained showed that it has slightly different between the experiment and simulation. The average velocity of the experiment was 0.223m/s while the numerical simulation was 0.256m/s. Through the chart coefficient of determination between experimental observation and simulation velocity, the R2 value was approximately 0.9. Thus, the simulation value are acceptable. Based on the case that has been proved, it can be concluded that the SPH numerical simulation can be used in this study.

Sarawak Barrage has been simulated for three cases in which different water level at the downstream have been implemented to get the velocity of the water flow and scouring profile. The maximum scouring was 0.13m depth which simulated for Case 3. The minimum scouring depth among the three cases was 0.05m which is for Case 2. From the scouring profile, the different level of water between upstream and downstream influence the scouring depth of the sediment. Besides that, flow velocity of water also affected due to differ of the water level at upstream and downstream. The maximum velocity of water at the barrage gate was 0.9m/s for case 3 while the lowest velocity was Case 2 which is 0.73m/s. Hence, it can be concluded that the higher the velocity of water from upstream, the higher the scouring depth at downstream when there was much difference in water level between upstream and downstream. The result obtained from this study was logically can be accepted due to the normal phenomenon. From the simulation result, improvement can be made to the site to mitigate all the problems.

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