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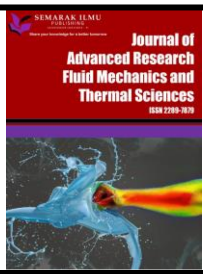


# Discrete Particle Method Numerical Simulation on The Distributions of Suspended Particles in The Flow of Ogee Spillway Structure

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**ABSTRACT**

Dam failure is undeniably catastrophic and one of its major causes is the soil erosion near the dam structure. In this paper, the characteristics and compositions of soil sediment in dam spillway structure were investigated to determine its impact on the occurrence of erosion. Four suspended samples were taken from the vicinity of Ogee dam spillway. Sediment analysis using scanning electron microscope revealed that the soils consist of relative high metal contents of aluminium, iron and magnesium. These metals will attribute to the erosion of dam wall, which subsequently reduce the durability of wall against high hydrostatic pressure exerted by the reservoir. Nonetheless, as the average sizing of suspended particles at each sampling location were capped at 4.55 µm, the damages incurred to the dam were minimal. Additionally, the suspended particles around the dam spillway was numerically simulated with the inclusion of discrete phase model. The numerical data were in great consensus with the corresponding finding attained from the particle image velocimetry experimental of a scaled-down dam model, with the discrepancy not more than 4.89 %. The movement of suspended particles due to the water flow can be tracked numerically and it is found the sediment prone to accumulate at the vicinity of dam spillway.

## 1. Introduction

In the recent years, there has been a significant increase of interest on simulation of granular materials, specifically sand, using different methods and elements for represent the sand and its properties. Kim *et al.*, revealed that scanning electron microscope (SEM), X-ray diffraction (XRD), energy dispersive X-ray (EDX) spectroscopy and mapping analyses were implemented to identify the creation of calcium carbonate and the characteristics of cementation of soil [1]. This study is supported by the findings by DeJong *et al.*, [2] and Scimeca *et al.*, [3] where the results from SEM and EDX provide clear images of the particles and quantitative analysis of the specimens.

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In another study of civil dam related problems, the comprehensive evaluation method by using XRF, XRD, SEM, and EDS was applied to investigate the mechanism of the concrete degradation [4]. This is supported by the study of Silva *et al*., where it explains that microscopy is the only technique capable to clearly identify the features associated with DEF in concrete [5]. A scouring study by Castillo and Carrillo, shows that similar results have been obtained by solving the problem from three different perspectives: empirical formulations, pressure fluctuations-erodibility index and CFD simulations [6]. Another study by Kitamur and Takagi, uses field observations, mathematical model tests and several hydraulic scale models [7]. Additionally, two vertical 2-dimensional partial models with a scale of 1/50 and a fully 3-dimensional model with a scale of 1/50 of the movable riverbeds at and around the dam 1.5 km upstream and downstream were used [7]. Empirical and semi-empirical equations were found to be the most reliable tools in the prediction of maximum scour depth [8].

Bell *et al*., simulated the granular materials of sand and grains by modelling the particles as discrete elements and had verified experimentally [9]. One of the significant advantages of this method is that dynamic phenomena, like splashes and avalanches, can be generated by particles' interaction with high physical accuracy [10]. This simulation technique is based on the molecular dynamics method which involve handling the constant forces efficiently. The technique of discrete element proposed is represented by multiple round particles that move together as a single rigid object. As the outcome, the particles can withstand the collision with other objects in a rigid body simulation system with realistic results. In contrast to the above rigid body approach, Zhu and Robert introduced a combination of particle-in-cell (PIC) and fluid-implicit-particle (FLIP) methods to simulate sand as fluid [11]. Alduán *et al*., proposed an improved technique for simulating granular materials with particles that achieves high visual resolution and at a lower computational cost than earlier techniques. Their main difference is detected on the simulation of the internal and external forces of granular materials [12].

C. Kloss *et al*., revealed that the best physics of granular materials is captured with discrete element method (DEM) but can be computationally time consuming. Therefore, discrete phase model (DPM) is needed to complement with DEM for disperse granular flow in order to accelerate the overall simulation [13]. This study seeks to analyse the effect of complementing DEM and DPM in CFD method. Through the computational scheme of DEM, all particles in the computational domain are tracked in a Langrangian approach, explicitly solving each particle's trajectory, based on corresponding momentum balances for translational and angular accelerations [14]. The DEM is an approach to numerical simulation that computes the motion of a large number of particles from the individual motion of each particle and their mutual interactions. There are limited studies in DEM method due to the issue of handling a large number of particles, which substantially increased the required computational costs [15-17]. In most cases, the DEM was not used in real time application. However, Maknickas *et al*., have proposed a parallelization of the DEM method to overcome the problem of the simulation cannot run in an acceptable frame rate if the number of particles is increased significantly [18].

Various image tracking experiments have also been introduced, for instance the particle image velocimetry (PIV). PIV is a non-intrusive experimental method to visualize the fluid flow velocity vector. The working principle of PIV revolves around the addition of seeding particles in the fluid flow that acts as the tracking particles. The movement of tracking particles upon being illuminated were recorded and the velocity of fluid flow can be calculated based on the instantaneous changes in particle position [19]. The capability of PIV as a flow velocity visualization tool had been proved viable in various applications, such as dynamic filtration unit [20], ogee spillway crest [21], flip-chip packaging [22,23], sediment bypass tunnel [24] and stepped spillway [25].

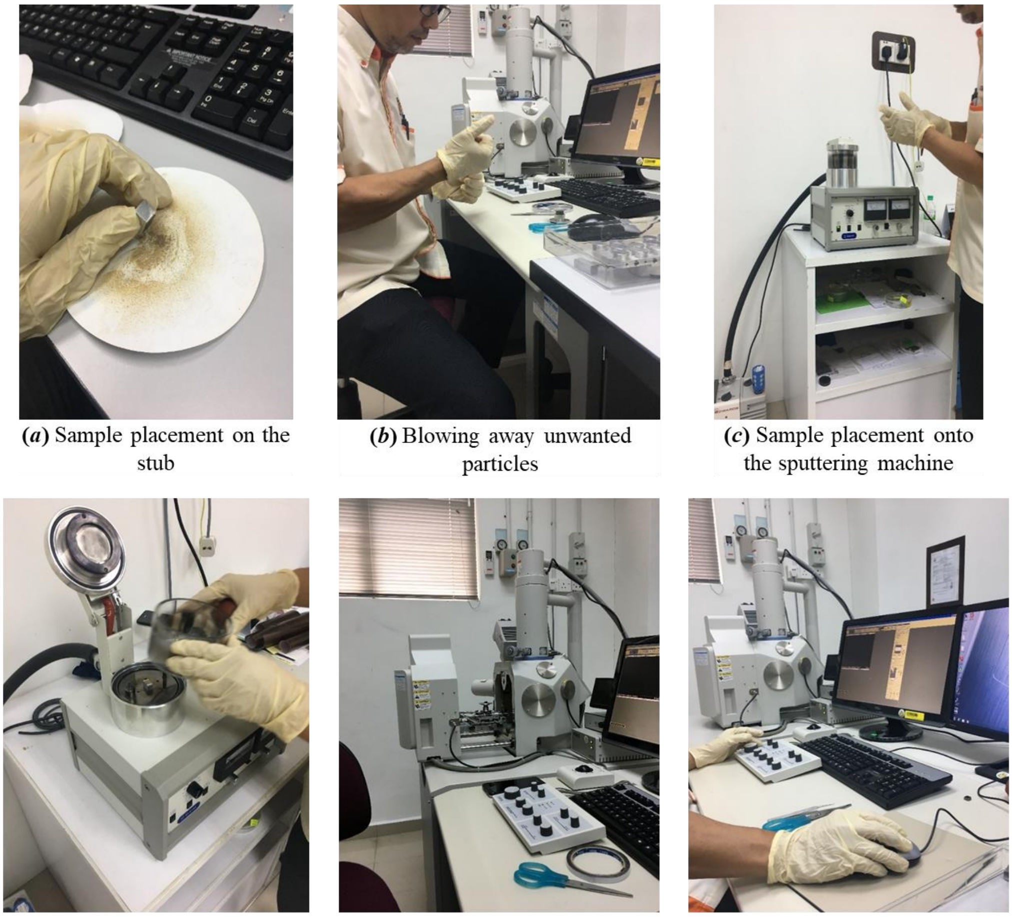
To date, there is no comprehensive study that investigates the compositions of soil sediment microscopically to correlate with the erosion profile. While there is vast amount of fluid-structure interaction (FSI) numerical simulations conducted to access the structural integrity and reliability of a dam spillway structure [26-28], the inclusion of suspended particles and therefore its effect on dam has scarcely been reported. To the best knowledges of authors, there is no study being reported on fluid particle dam reliability that emphasize on suspended particles as well as its detailed suspended particle compositions. This paper herewith presents the effect of suspended particles and its compositions on the dam reliability. Moreover, the problem on dam suspended particles will be numerically simulated using the discrete phase model (DPM) to visualize the particle tracks of suspended particles.

## 2. Suspended Particles Characterization Using Scanning Electron Microscope

To study the impact of sediment and suspended compositions on the downstream depositions and erosion, it is essential to conduct the composition characterization analysis on the sediment microscopically. The compositions of sediment samples collected from four random different locations, respectively labelled as points 1 to 4, were identified using the scanning electron microscope (SEM). The section of four distinct sampling location is to ensure more accurate averaged material compositions at the downstream.

The overall process flow of the sediment samples analysis was summarized in Figure 1. Prior SEM profiling, the sediment samples required thorough preparations which includes cleaning and sputtering. The pre-processing stage was initiated by affixing the sediment samples onto the sample stub. Carbon tape was used to adhesively bond the sample to the stub. Impurities on the sediment samples were then removed using a blower. Later, the sample was placed into the sputtering machine for 30 seconds at the operating pressure of 70 mTorr. The sample will be coated with a thin layer of gold. This sputtering process was carried out to enhance the conductivity of sediment sample for which its primary constituent is non-conductive silica.

Subsequently, the gold-sputtered stub was transferred to the sample compartment of the SEM. The operation of SEM was controlled by the software. Next, the desire operating voltage ranging from 1 kV to 30 kV was selected to attain necessary magnification and sharpness. Lastly, all required imaging and measurements on the sediment samples were taken alongside with the sediment compositions.



(*a*) Sample placement on the stub
(*b*) Blowing away unwanted particles
(*c*) Sample placement onto the sputtering machine
(*d*) Sample stub removal from sputtering machine
(*e*) Sample placement into the SEM sample compartment
(*f*) Sample analysing using SEM software

**Fig. 1.** General process flow of analysing the sediment sample using sputtering machine and scanning electronic microscope (SEM)

## 3. Numerical Modelling of Suspended Particles

This section detailed the numerical simulation of suspended particles in the dam spillway using the commercially available finite volume method (FVM) software, ANSYS. In this simulation, the fluid-particle interaction between the fluid flow of continuous phase and dam structure will be considered together with the sediment soils as particulate phase. The three ANSYS modules participated in this simulation of suspended particles are ANSYS Fluent, ANSYS Structural and System Coupling.

The continuous fluid phase was governed by the Navier-Stokes equations, which comprises of the continuity equation and momentum equation, respectively given as

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathrm{u}) = 0, \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \mathrm{u}) + \nabla(\rho \mathrm{u} \cdot \mathrm{u}) = -\nabla P + \nabla \tau + \rho g, \tag{2}$$

where $t$ is the time, $\rho$ is the fluid density, u is the flow velocity, $\tau$ is the shear stress and gravitational acceleration, $g$ [29-32].

Moreover, to track the instantaneous flow front, the multiphase volume of fluid (VOF) model is setup based on the implicit scheme. The primary and secondary phases are air and water respectively. Both these phases are indicated using the parameter of volume fraction of secondary phase, $f$, ranging from 0 to 1. VOF model is governed by the transport equation

$$\frac{\partial \rho}{\partial t} f + \mathrm{u} \cdot \nabla f = 0, \tag{3}$$

The particulate phase of sediment presented in water was modelled by the discrete phase model (DPM). By the forces balance, the trajectory of the sediment particles as suspended in the water can be determined with known particle's velocity, $\mathrm{u}_p$

$$\frac{\partial}{\partial t} \mathrm{u}_p = \frac{18\mu_f}{d_p \rho_p C_c}\left(\mathrm{u} - \mathrm{u}_p\right) + \vec{\mathrm{g}}\frac{\rho_p - \rho}{\rho_p} + \vec{F}_x, \tag{4}$$

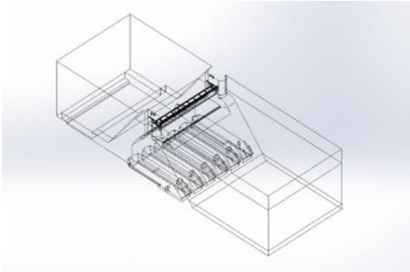
where $\mu_f$ is the dynamic viscosity of the fluid, $\rho_p$ is density of particle, $d_p$ is the diameter of particle and $C_c$ is the Cunningham correction factor [17]. The additional force acting on the sediment particle, $F_x$ is related to the mass, acceleration and pressure gradient in the fluid for $\rho > \rho_p$ and is given as

$$F_x = \mathrm{u}_p \frac{\rho}{\rho_p} \frac{\partial \mathrm{u}}{\partial x}. \tag{5}$$

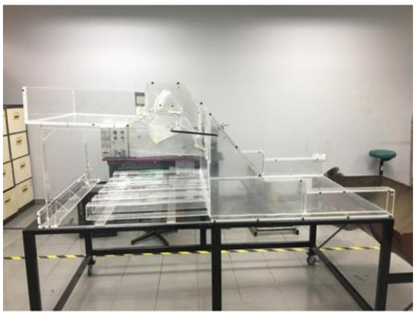
Generally, the CAD model consists of two major parts, namely the upstream and the downstream. The model is constructed using SolidWorks with a scale of 1: 40 compared to the actual Ogee dam. The individual parts of the dam with scaled down dimensions were formed by considering the complexity of the geometry. The dam model is then created via SolidWorks and fabricated as shown in Figure 2.

The environment of conventional flow process is replicated in Ansys FLUENT using two-way interactions of multiphase VOF and DPM model. A scaled down three-dimensional model of a dam was constructed and will undergo a two-way interaction with the water. The discrete particle phase will enable precise prediction of the trajectory particles. The schematic diagram and mesh model of the scaled down dam are represented in Figure 3. The mesh developed for the current model is based on tetrahedrons mesh. The semi-implicit method (SIMPLE) algorithm scheme was chosen as the solver for both pressure and velocity coupling to obtain accurate result [31 – 32].

The fluid domain divided into three parts which are air, water and sediment. The zones of the boundary conditions in the ANSYS Fluent set-up are inlet, outlet and the rest are set as the no-slip wall condition as shown in Figure 3. For the mixture phase of the inlet, velocity inlet boundary conditions are used to define the velocity and scalar properties of the flow. The magnitude of the velocity of the water flow into the inlet is set at 0.0075 m/s so that it is nearly negligible and does not have a huge effect on the fluid flow. No-slip wall condition was imposed such that the relative wall-fluid velocity is zero and ensured that there would not be any flow across the boundary. Moreover, both the pressures at the inlet and outlet equal the atmospheric pressure which is 0 Pa (gauge).



(*a*) CAD model of dam spillway



(*b*) Fabricated physical model

**Fig. 2.** Dam spillway model (a) generated from CAD software and (b) fabricated physically

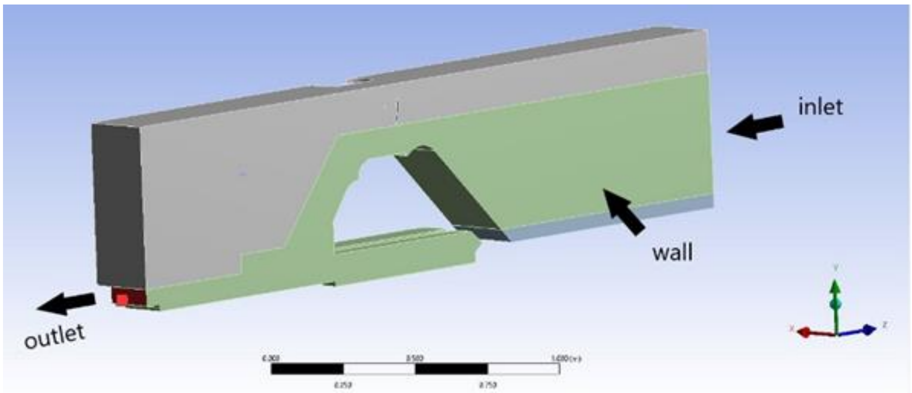



**Fig. 3.** The boundary conditions assigned on the fluid domains in the numerical simulation

## 4. Particle Image Velocimetry (PIV) Experiment

Figure 4 presents the particle image velocimetry (PIV) experimental setup for conducting the validation process on dam's physical model. In setting up, a camera video is placed perpendicularly to the laser to record the flow of water from the side. Considerable amount of polyamide seeding particles were added to the water as tracking particles, to be illuminated by the thin laser sheet. Upon commencing the experiment, the ambient is kept dark to ensure the camera is capturing the thin illuminated sheet. Subsequently, the images acquired will be analysed using PIVlab software to obtain the flow velocity and flow vectors. Image pre-processing was conducted to enhance the quality of images and to select area of interest through masking procedure. Afterward, the calibration stage was carried out by setting the scale of one pixel and the time interval between two subsequent shots. For the current experiment, the time interval is set to be 81 ms. Finally, the contours of velocity and vector field for spillway flow can then be obtained.

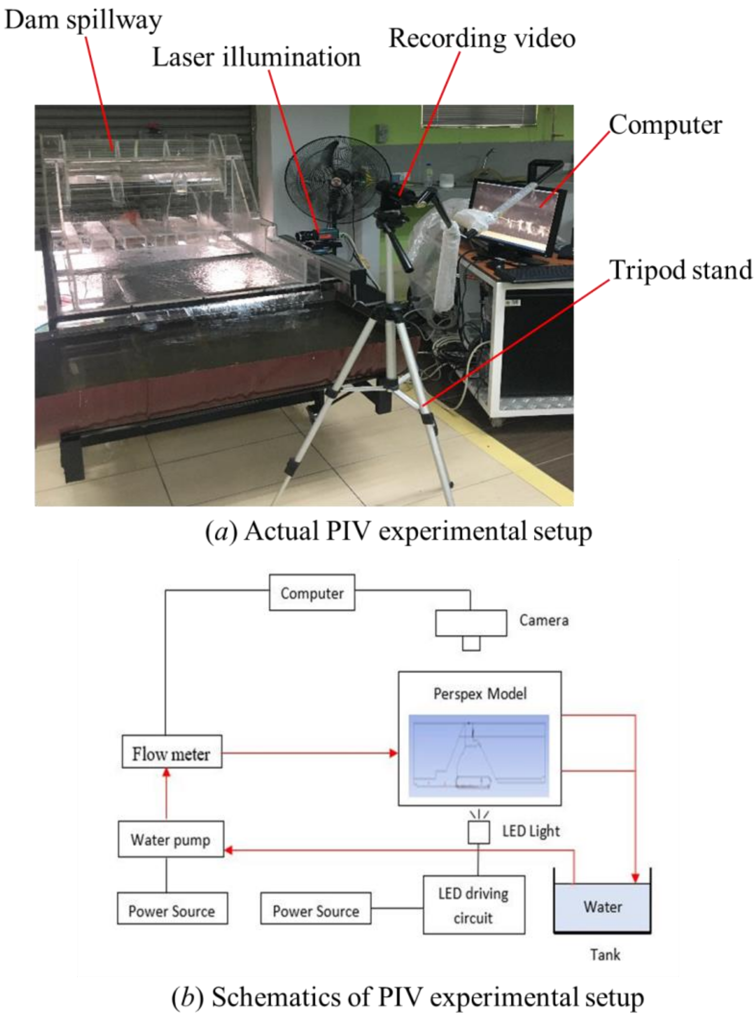



**Fig. 4.** The experimental particle image velocimetry (PIV) setup to visualize the streamlines of water flow in the dam spillway

## 5. Results and Discussion
### *5.1 Sediment Characterization Analysis*

Figure 5 to Figure 8 depict the findings obtained from the SEM characterization analysis on the sediment specimens collected in location 1, location 2, location 3 and location 4 respectively. The sizes of sediment particles were measured using the microscopic imagery. In each sampling locations, two spots were selected to have their element compositions analysed and identified. Additionally, the spectrometry of compositions was obtained.

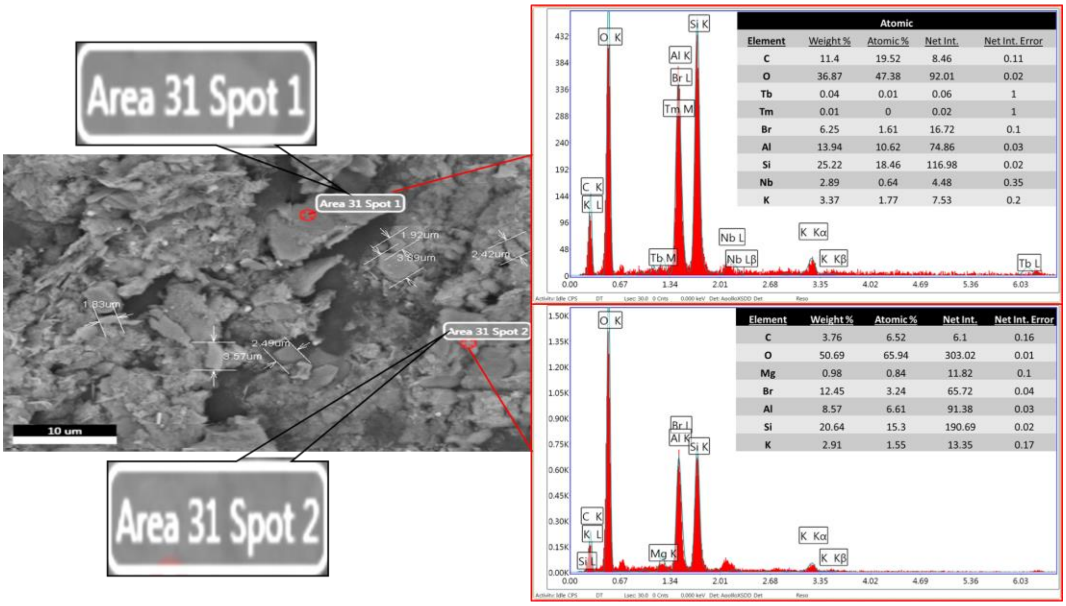



**Fig. 5.** The SEM image, area spot and composition analysis for the sediment specimen collected in the location 1

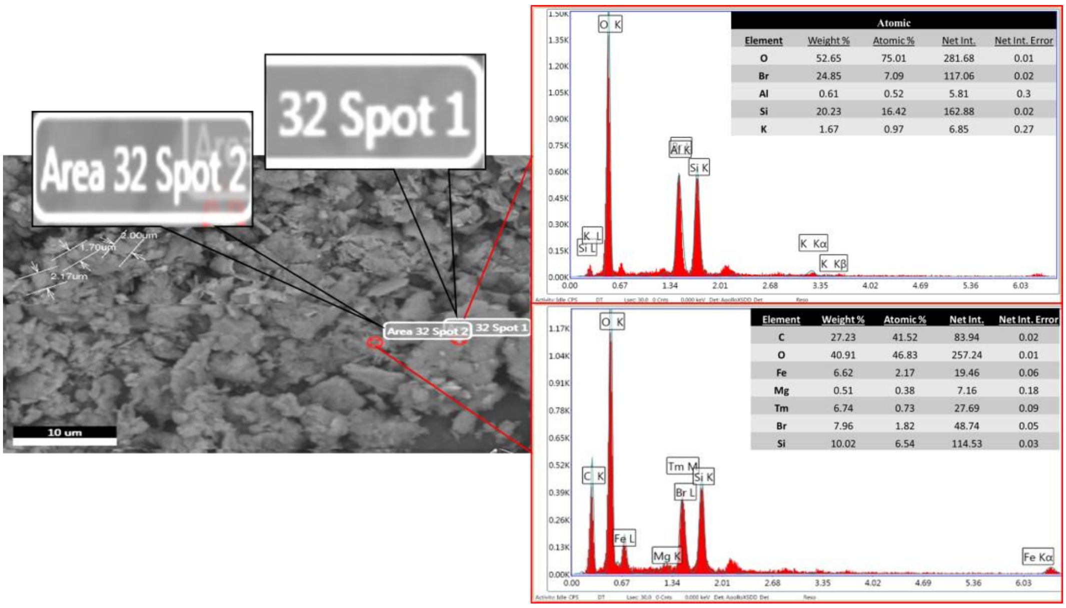



**Fig. 6.** The SEM image, area spot and composition analysis for the sediment specimen collected in the location 2

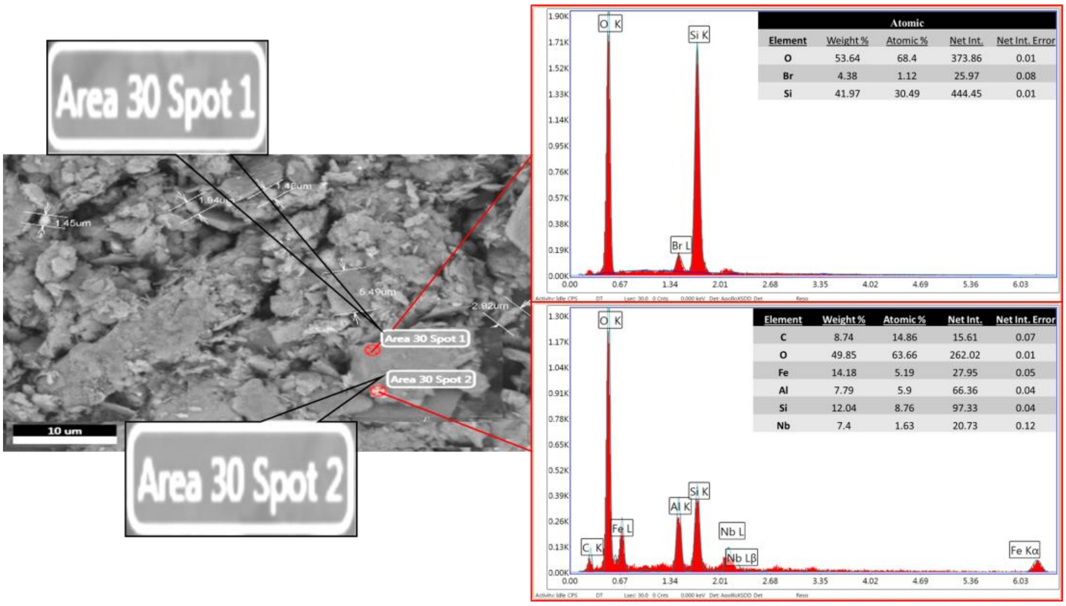



**Fig. 7.** The SEM image, area spot and composition analysis for the sediment specimen collected in the location 3

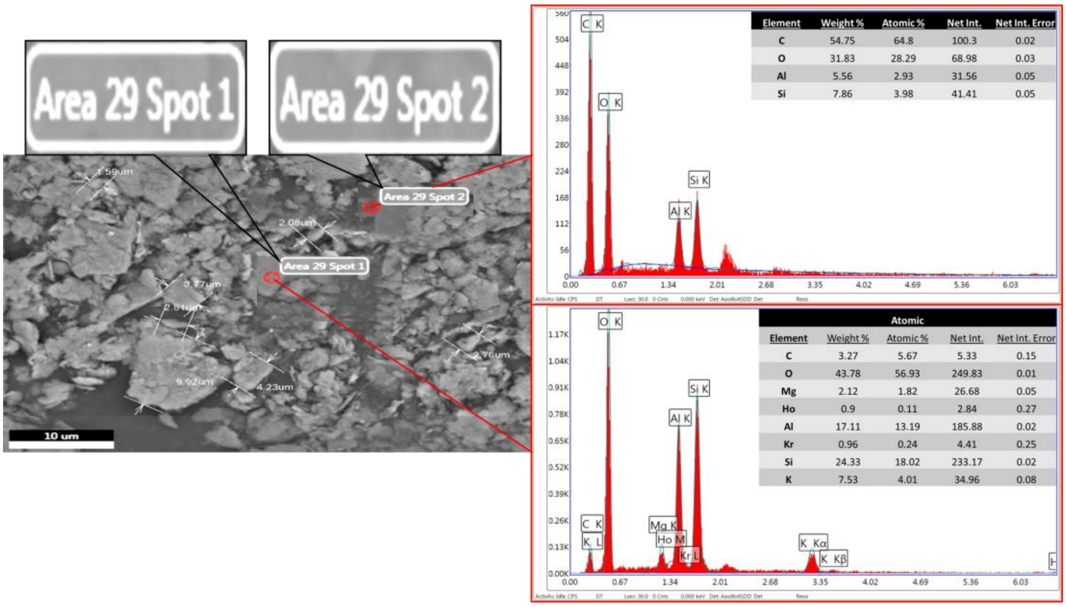



**Fig. 8.** The SEM image, area spot and composition analysis for the sediment specimen collected in the location 4

Based on the sediment SEM analysis shown in Figure 6 to 9, the maximum size of particle at location 1 is 4.55 $\mu$m while the average size of the particles is 3 $\mu$m. At location 2, the maximum size is bigger than location 1 by 0.68 $\mu$m and the average size is also 3 $\mu$m. Additionally, the average size of particles at location 3 and location 4 are 2.8 $\mu$m and 3.8 $\mu$m respectively. The particles are relatively small so it will not cause too much damage to the structure. However, if the particles are big, it will be harmful to the structure as it leading to pitting at the wall of the dam. Big sizes particles also will lead to clogging in the dam turbine and penstock. Moreover, larger particles tend to sink downward whereas smaller particles would be floating on the water due to the buoyancy.

Generally, there are particles with various type of elements present in different locations. For example, at location 1 (spot 1), the sample is made from various elements such as aluminium (Al), niobium (Nb), bromine (Br), terbium (Tb), thulium (Tm), potassium (K) and silicone (Si). carbon (C) and oxygen(O) also exist in the sample however we can neglect both elements due to the oxidation. Both of O and C peaks are the result from the oxidation. Silicone (Si) is the dominant element in the sample with 25.22 wt.% followed by aluminium (Al) and bromine (Br) with 13.94 wt.% and 6.25 wt.% respectively. While in spot 2, the particle is made of from aluminium (Al), bromine (Br), potassium (K), magnesium (Mg) and silicone (Si). The weightage of the elements is as following, Al (8.57 wt.%), Br (12.45 wt.%), K (2.91 wt.%), Mg (0.98 wt.%) and the major element is Si with 20.64 wt.%.

The sediment composition at location 2 (spot 1) shows the particle is made up from similar elements with location 1 (spot 2) but without Mg. However, the major element for this particle is Br with 24.85 wt.% followed by Si (20.23 wt.%), K (1.67 wt.%) and Al (0.61 wt.%). While at spot 2, the chemical composition shows the particle contains iron (Fe), magnesium (Mg), bromine (Br), thulium (Tm), and silicone (Si). The weightage of the element is quite low due to oxidation where Si only shows a value of 10.02 wt.%. In the location 3 (spot 1), the particle is a combination of Si and Br where Si is the dominant element with 41.97 wt.%. While at spot 2, the mixture of the particle consists of iron (Fe), aluminium (Al), niobium (Nb) and nilicone (Si). The main component of this particle is Fe with a weightage of 14.18 wt.%. The weightages of the other elements are Si (12.04wt%), Al (7.79%) and Nb (7.4 wt.%). From the analysis at location 4 (spot 1), it shows that Si is the highest element weightage there with 24.33 wt.% followed by Al (17.11 wt.%). Moreover, in spot 2, there are only two elements shown beside carbon and oxygen. Si has 7.86 wt.% while 5.56 wt.% for Al.

The most abundant element in the soil sediment is silicon, that presents in its oxidise state of silica. Generally, the sand tends to deposit at the bottom of upstream and potentially leads to the clogging issue at penstocks. There is also abundant number of metal elements like aluminium, iron and magnesium. These metals would erode the wall of the dam which will reduce the durability of the wall to withstand the high pressure. For instance, high number of metal element at location 1 will affect the structure wall with an eroding effect as it is near to the wall of gate. It is inferred that the erosion effect of sediment on the dam structure is highly dependent on the compositions of sediment, size and weight of sediment particles. Generally, metals tend to erode the dam structure while silica would clog the penstocks and causes depositions. Furthermore, larger and heavier sediment particles tend to sink at the downstream causing depositions. Smaller and lighter sediment particles would float on the water and interacting the dam wall, thus causes structural erosion.

### *5.2 Suspended Particles*
#### *5.2.1 Validations*

Figure 9 depicts the three regions of interest on the spillway where the flow velocities were probed and averaged. Moreover, both the experimental and numerical flow contours at the three regions were compared qualitatively as shown in Figure 9. Based on Table 1, the discrepancy between numerical and experimental averaged flow velocity probed at the region 1 is 4.89%; meanwhile the discrepancies at the region 2 and region 3 are 2.26 % and 0.30% respectively. Generally, both PIV experiment and numerical simulation achieved great consensus. At the region 2, the high flow velocity with swirling vortex was observed since it was the downstream region where the water from the upstream falls on. This is on contrary to the laminar and steady flows shown in both region 1 and region 3.

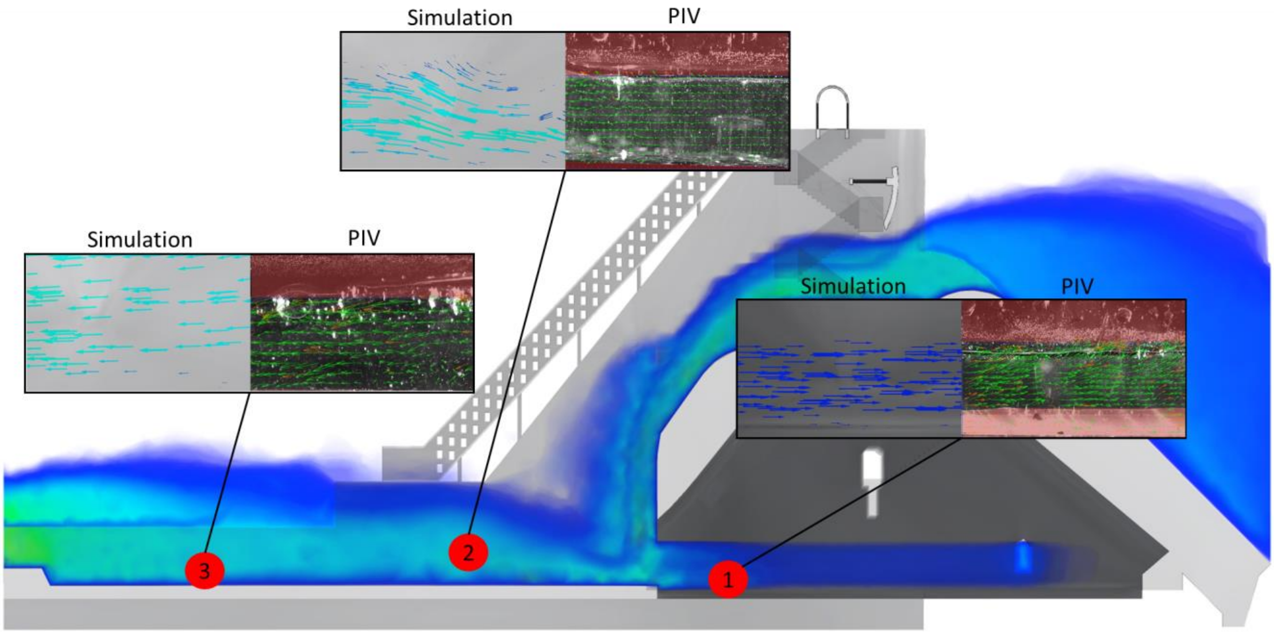



**Fig. 9.** Qualitative comparison between numerical and experimental flow profiles at three regions of dam spillway

**Table 1**
Quantitative comparison between the numerical and experimental averaged flow velocity probed at three regions of interest

| Region of interest | Averaged flow velocity (m/s) | | Discrepancy (% deviation) |
|---|---|---|---|
| | Numerical simulation | PIV experiment | |
| 1 | 0.386 | 0.404 | 4.89 |
| 2 | 0.512 | 0.501 | 2.26 |
| 3 | 0.375 | 0.374 | 0.30 |

*5.2.2 Suspended particle track*

Figure 10(a) shows the result from the simulation for pressure contour whereby the pressure is higher at the bottom of the upstream and gradually decrease with increasing height. This is due to hydrostatic pressure phenomenon. In another view, the pressure is lower at the gate which is inversely proportional to the higher mass flow. the velocity of particle is higher at the downstream as compared to upstream. Figure 10(b) depicts the concentration of the particles at the dam. It showed that particles will accumulate at the certain area of downstream region. This deduced that the particles move at high speed of velocity at the gate then stuck after they reach the ground. Consequently, the particles will be concentrated at the region after they pass through the gate. Figure 10(c) shows that there is high particle concentration on the downstream near the spillway structure. This had affirmed the tendency of sediment particles to accumulate nearby the structure, which may prone to the structural erosion, as the previous compositions characterization analysis revealed the presence of metals in the sediment specimens.

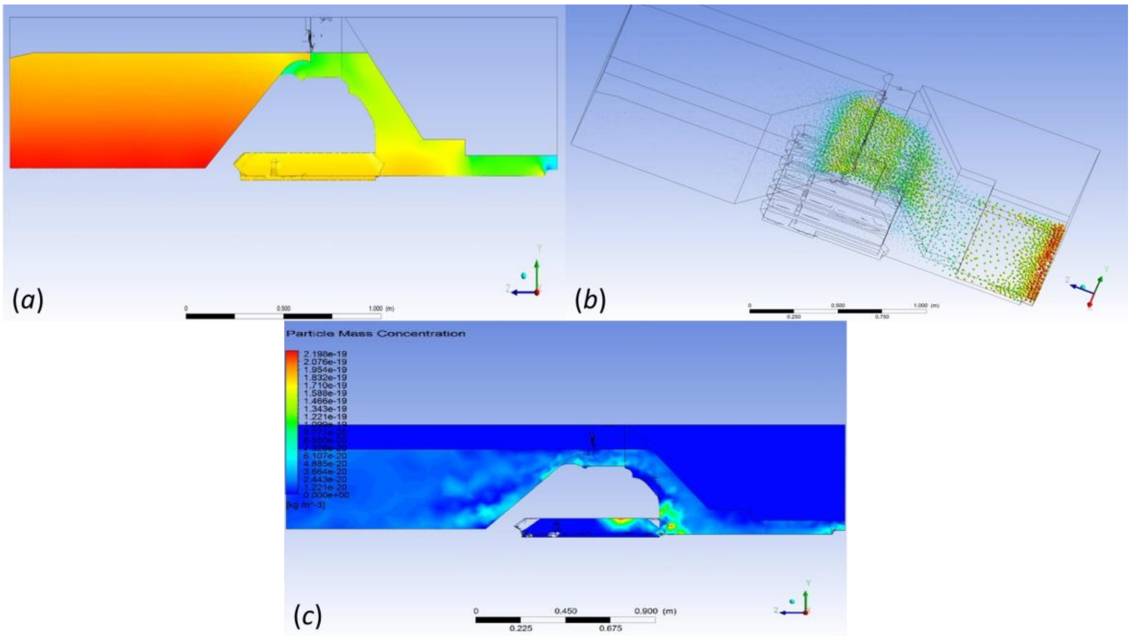



**Fig. 10.** (a) Pressure contour, (b) suspended particle track and (c) particle mass concentration contour

## 6. Conclusions

This work studied the sediment in an Ogee dam spillway to understand how it contributes to the soil erosion, from the two distinct viewpoints of sediment compositions characterization and suspended particles transport modelling. The current paper presents a case study of Ogee dam. Using scanning electron microscope (SEM), the sediment specimens collected have their compositions characterized. It is found that the silicon element that exists in the form its oxide being the major constituent of the soil sediments and would causes the deposition at the bottom of the upstream and penstocks clogging. Furthermore, the sediment contains various metals, for instance aluminium, iron and magnesium. These metals have eroding effect on the dam wall, thus reduce the strength of the wall to withstand the high pressure. It is justified both the sediment sizing and compositions were the parameters determining the depositions and erosions on dam structure. Subsequently, a three-dimensional fluid particle interaction numerical model was established to simulate suspended particles at dam using discrete phase model (DPM). The fluid flow including the velocity and pressure were analysed in addition to the track of sediments particles. The numerical results were well-validated to the particle image velocimetry (PIV) experiment, such that both findings were comparable. Both the velocity fields and flow vector attained numerically and experimentally qualitatively similar. Quantitatively, the discrepancy in magnitude of flow velocity is less than 4.89 %. Therefore, the current numerical model is viable in visualizing the suspended particles in dam from both macroscopic aspect of water flow and microscopic aspect of sediment particle tracks, as a vital part of dam reliability analysis. It was found that the sediment particles tend to accumulate near the vicinity of spillway structure at the downstream shortly after passing through the gate, which may leads to potential structural erosion with the present of metals found from the previous analysis. In summary, this paper provides both microscopic and macroscopic insights on the effects of sediment composition and suspended particles, from both aspects of material and fluid dynamics to understand the sediment erosion which ultimately leads to dam failure.

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## References
[1] Kim, Daehyeon, Kyungho Park, and Dongwook Kim. "Effects of ground conditions on microbial cementation in soils." *Materials* 7, no. 1 (2013): 143-156. https://doi.org/10.3390/ma7010143
[2] DeJong, Jason T., Michael B. Fritzges, and Klaus Nüsslein. "Microbially induced cementation to control sand response to undrained shear." *Journal of geotechnical and geoenvironmental engineering* 132, no. 11 (2006): 1381-1392. https://doi.org/10.1061/(ASCE)1090-0241(2006)132:11(1381)
[3] Scimeca, Manuel, Simone Bischetti, Harpreet Kaur Lamsira, Rita Bonfiglio, and Elena Bonanno. "Energy Dispersive X-ray (EDX) microanalysis: A powerful tool in biomedical research and diagnosis." *European journal of histochemistry: EJH* 62, no. 1 (2018). https://doi.org/10.4081/ejh.2018.2841
[4] Zhu, Xufen, Ji Li, Yi Zhang, Hanzhou Song, and Hu Zheng. "The Sulphate Effect on Lijiaxia Concrete Dam (China) Gallery." *Journal of Chemistry* 2017 (2017). https://doi.org/10.1155/2017/8698759
[5] Silva, António Santos, D. Soares, L. Matos, Manuela M. Salta, Loïc Divet, Alexandre Pavoine, António Estevao Candeias, and José Mirão. "Influence of mineral additions in the inhibition of delayed ettringite formation in cement based materials–A microstructural characterization." In *Materials Science Forum*, vol. 636, pp. 1272-1279. Trans Tech Publications Ltd, 2010. https://doi.org/10.4028/www.scientific.net/MSF.636-637.1272
[6] Castillo, Luis G., and José M. Carrillo. "Scour, velocities and pressures evaluations produced by spillway and outlets of dam." *Water* 8, no. 3 (2016): 68. https://doi.org/10.3390/w8030068
[7] Kitamura, Y., and S. Takagi. "Hydraulic study on scouring downstream of Funagira Dam spillway apron (Japan)." (2016). https://doi.org/10.1201/9781315375045-79
[8] Comiti, F., M. A. Lenzi, and L. Mao. "Local scouring at check dams in mountain rivers." *Check dams, morphological adjustments and erosion control in torrential streams. Nova Publ., Hauppauge, NY, USA* (2010): 263-82.
[9] Bell, Nathan, Yizhou Yu, and Peter J. Mucha. "Particle-based simulation of granular materials." In *Proceedings of the 2005 ACM SIGGRAPH/Eurographics symposium on Computer animation*, pp. 77-86. 2005. https://doi.org/10.1145/1073368.1073379
[10] Belostosky, Alexander M., Pavel A. Akimov, Taymuraz B. Kaytukov, Irina N. Afanasyeva, Anton R. Usmanov, Sergey V. Scherbina, and Vladislav V. Vershinin. "About finite element analysis of fluid–structure interaction problems." *Procedia Engineering* 91 (2014): 37-42. https://doi.org/10.1016/j.proeng.2014.12.008
[11] Zhu, Bo, and Xubo Yang. "Animating Sand as a Surface Flow." In *Eurographics (short papers)*, pp. 9-12. 2010. https://doi.org/10.1145/1073204.1073298
[12] Alduán, Iván, Angel Tena, and Miguel A. Otaduy. "Simulation of High-Resolution Granular Media." In *CEIG*, pp. 11-18. 2009. http://dx.doi.org/10.2312/LocalChapterEvents/CEIG/CEIG09/011-018
[13] Kloss, Christoph, Christoph Goniva, Georg Aichinger, and Stefan Pirker. "Comprehensive DEM-DPM-CFD simulations-model synthesis, experimental validation and scalability." In *Proceedings of the seventh international conference on CFD in the minerals and process industries*, CSIRO, Melbourne, Australia, pp. 9-11. 2009.
[14] Evans, E., and A. C. Wilcox. "Fine sediment infiltration dynamics in a gravel-bed river following a sediment pulse." *River research and applications* 30, no. 3 (2014): 372-384. https://doi.org/10.1002/RRA.2647
[15] Zahari, N. M., M. H. Zawawi, L. M. Sidek, Daud Mohamad, Zarina Itam, M. Z. Ramli, Agusril Syamsir, Aizat Abas, and M. Rashid. "Introduction of discrete phase model (DPM) in fluid flow: a review." In *AIP Conference Proceedings*, vol. 2030, no. 1, p. 020234. AIP Publishing LLC, 2018. https://doi.org/10.1063/1.5066875
[16] Azman, Aqil, N. M. Zahari, M. H. Zawawi, M. H. Mansor, F. C. Ng, Aizat Abas, F. Nurhikmah, and Nurhanani A. Aziz. "The Impact of Vortex Formation Due to The Operational Dam Condition: A Review." In *IOP Conference Series: Materials Science and Engineering*, vol. 920, no. 1, p. 012025. IOP Publishing, 2020. https://doi.org/10.1088/1757-899X/920/1/012025
[17] Ng, Fei Chong, Aizat Abas, Z. L. Gan, Mohd Zulkifly Abdullah, F. Che Ani, and M. Yusuf Tura Ali. "Discrete phase method study of ball grid array underfill process using nano-silica filler-reinforced composite-encapsulant with varying filler loadings." *Microelectronics Reliability* 72 (2017): 45-64. https://doi.org/10.1016/j.microrel.2017.03.034
[18] Maknickas, Algirdas, Arnas Kačeniauskas, Rimantas Kačianauskas, Robertas Balevičius, and Algis Džiugys. "Parallel DEM software for simulation of granular media." *Informatica* 17, no. 2 (2006): 207-224. https://doi.org/10.15388/Informatica.2006.13
[19] Zahari, Nazirul Mubin, Mohd Hafiz Zawawi, Fei Chong Ng, Mohamad Aizat Abas, Farah Nurhikmah, Nurhanani Abd Aziz, Lun Hao Tung, Iszmir Nazmi Ismail, Lariyah Mohd Sidek, and Mohd Rashid Mohd Radzi. "Finite Volume Method

Numerical Modelling of the Penstock Flows in Dam Intake Sector Subjected to Varying Operating Conditions with Particle Image Velocimetry Validation." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 86, no. 1 (2021): 176-186. https://doi.org/10.37934/arfmts.86.1.176186

[20] Xie, Xiaomin, Claude Le Men, Nicolas Dietrich, Philippe Schmitz, and Luc Fillaudeau. "Local hydrodynamic investigation by PIV and CFD within a Dynamic filtration unit under laminar flow." *Separation and Purification Technology* 198 (2018): 38-51. https://doi.org/10.1016/j.seppur.2017.04.009

[21] Peltier, Yann, Benjamin Dewals, Pierre Archambeau, Michel Pirotton, and Sebastien Erpicum. "Pressure and velocity on an ogee spillway crest operating at high head ratio: experimental measurements and validation." *Journal of Hydro-environment Research* 19 (2018): 128-136. https://doi.org/10.1016/j.jher.2017.03.002

[22] Ng, Fei Chong, Aizat Abas, and Mohd Zulkifly Abdullah. "Effect of solder bump shapes on underfill flow in flip-chip encapsulation using analytical, numerical and PIV experimental approaches." *Microelectronics Reliability* 81 (2018): 41-63. https://doi.org/10.1016/j.microrel.2017.12.025

[23] Ng, Fei Chong, Aizat Abas, Ismail Abustan, Z. Mohd Remy Rozainy, M. Z. Abdullah, and Sharon Melissa Kon. "Visualization of Underfill Flow in Ball Grid Array (BGA) using Particle Image Velocimetry (PIV)." In *IOP Conference Series: Materials Science and Engineering*, vol. 370, no. 1, p. 012064. IOP Publishing, 2018. https://doi.org/10.1088/1757-899X/370/1/012064

[24] Kantoush, Sameh, Tetsuya Sumi, and Mitsuhiro Murasaki. "Evaluation of sediment bypass efficiency by flow field and sediment concentration monitoring techniques." *Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)* 67, no. 4 (2011): I_169-I_174. https://doi.org/10.2208/jscejhe.67.I_169

[25] Azman, Aqil, Fei Chong Ng, Mohd Zawawi, Aizat Abas, Mohd Rozainy MAZ, Ismail Abustan, Mohd Adlan, and Wei Loon Tam. "Effect of barrier height on the design of stepped spillway using smoothed particle hydrodynamics and particle image velocimetry." *KSCE Journal of Civil Engineering* 24, no. 2 (2020): 451-470. https://doi.org/10.1007/s12205-020-1605-x

[26] Zawawi, Mohd Hafiz, F. C. Ng, Aqil Azman, L. H. Tung, Ismail Abustan, Z. Mohd Remy Rozainy, and Aizat Abas. "Reliability analysis on the reservoir dam spillway structure using fluid-structure interaction." In *IOP Conference Series: Materials Science and Engineering*, vol. 920, no. 1, p. 012030. IOP Publishing, 2020. https://doi.org/10.1088/1757-899X/920/1/012030

[27] Ng, Fei Chong, Aizat Abas, Ismail Abustan, Z. Mohd Remy Rozainy, M. Z. Abdullah, and Sharon Melissa Kon. "Fluid/structure interaction study on the variation of radial gate's gap height in dam." In *IOP Conference Series: Materials Science and Engineering*, vol. 370, no. 1, p. 012063. IOP Publishing, 2018. https://doi.org/10.1088/1757-899X/370/1/012063

[28] Nashurdin, Muhammad Naqib, Aizat Abas, Aqil Azman, F. C. Ng, M. R. M. Radzi, and A. Hassani. "Numerical visualization of flow in spillway and downstream of dam using fluid/structure interaction." In *AIP Conference Proceedings*, vol. 2129, no. 1, p. 020044. AIP Publishing LLC, 2019. https://doi.org/10.1063/1.5118052

[29] Ng, Fei Chong, Mohd Hafiz Zawawi, Lun Hao Tung, Mohamad Aizat Abas, and Mohd Zulkifly Abdullah. "Symmetrical unit-cell numerical approach for flip-chip underfill flow simulation." *CFD Letters* 12, no. 8 (2020): 55-63. https://doi.org/10.37934/cfdl.12.8.5563

[30] Ng, Fei Chong, Lun Hao Tung, Mohd Hafiz Zawawi, Muhamed Abdul Fatah Muhamed Mukhtar, Mohamad Aizat Abas, and Mohd Zulkifly Abdullah. "Effect of contact angle on meniscus evolution and contact line jump of underfill fluid flow in flip-chip encapsulation." *CFD Letters* 12, no. 6 (2020): 28-38. https://doi.org/10.37934/cfdl.12.6.2838

[31] Zahari, Nazirul Mubin, Mohd Hafiz Zawawi, Lariyah Mohd Sidek, Fei Chong Ng, Mohamad Aizat Abas, Farah Nurhikmah, and Muhammad Naqib Nashrudin. "Discrete Phase Modelling of Sediment Transport and Scouring of Suspended Particles in Dam Spillway." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 88, no. 2 (2021): 38-49. https://doi.org/10.37934/arfmts.88.2.3849

[32] Zahari, Nazirul Mubin, Mohd Hafiz Zawawi, Fei Chong Ng, Mohamad Aizat Abas, Farah Nurhikmah, Nurhanani Abd Aziz, Lun Hao Tung, Iszmir Nazmi Ismail, Lariyah Mohd Sidek, and Mohd Rashid Mohd Radzi. "Finite Volume Method Numerical Modelling of the Penstock Flows in Dam Intake Sector Subjected to Varying Operating Conditions with Particle Image Velocimetry Validation." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 86, no. 1 (2021): 176-186. https://doi.org/10.37934/arfmts.86.1.176186