FLUID-STRUCTURE INTERACTION (FSI) AND SEDIMENT TRANSPORT STUDY OF TNB HYDROPOWER STATION

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DECLARATION

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Date	: 29 May 2019	

Witnessed by

Supervisor	: Dr. Mohamad Aizat Abas	Signature :
Date	: 29 May 2019	

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LIST OF ABBREVIATION

DPM	Discrete Particle Method
DEM	Discrete Element Method
PIV	Particle Image Velocimetry
SEM	Scanning Electron Microscopic
CAD	Computer Aided Design
SPH	Smoothed Particle Hydrodynamics
FSI	Fluid Structure Interaction
TNB	Tenaga Nasional Berhad
CFD	Computational Fluid Dynamics
DREAM	Dam Removal Express Assessment Models
PIC	Particle-In-Cell
FLIP	Fluid-Implicit-Particle
LSPIV	Large Scale Particle Image Velocimetry
VOF	Volume of Fluid

ABSTRAK

Semasa zaman purba, empangan dibina semata-mata untuk bekalan air tetapi apabila manusia mula berkembang, fungsi empangan juga meningkat untuk memenuhi keperluan manusia. Dalam peredaran masa, satu masalah telah muncul yang menimbulkan banyak kesulitan di empangan. Masalahnya adalah disebabkan oleh sedimen. Pemendapan ini akan menjejaskan empangan dalam pelbagai perkara seperti keselamatan empangan dan mengurangkan pengeluaran tenaga, penyimpanan, kapasiti pelepasan dan keupayaan pelemahan banjir. Tujuan kajian ini adalah untuk mengkaji pergerakan pengangkutan sedimen di stesen janakuasa TNB iaitu Empangan Chenderoh. Model berskala dibina menggunakan SolidWorks dan kemudian direka untuk model fizikal. Simulasi model 3D dijalankan menggunakan ANSYS Interaction Structural Fluid. Perumusan yang digunakan adalah Kaedah Partikel Diskret (DPM), Kaedah Elemen Diskret (DEM) dan Navier-Stokes. Percubaan velocimetry imej zarah (PIV) juga akan dijalankan untuk mengesahkan keputusan simulasi. Akhirnya, keputusan seperti halaju dan arah aliran dibandingkan, mengakui persamaan yang hebat antara simulasi berangka dan ujian eksperimen. Juga, dalam kajian ini, sifat kimia sedimen dan saiznya dijumpai. Kesalahan peratusan tertinggi antara simulasi dan PIV ialah 4.89%. Di samping itu, kadar pelepasan tertinggi adalah 4.20E-9 kg / s manakala kadar pemendapan tertinggi adalah 2.00E-6 kg / s. Berdasarkan keputusan yang diperolehi, tempoh penyelenggaraan yang perlu dilakukan ialah setiap 8.9 tahun. Selain itu, kadar pemotongan juga dibincangkan dalam kajian ini. Hasil ini akan menjadi asas untuk meningkatkan pengangkutan sedimen di Empangan Chenderoh pada masa akan datang.

ABSTRACT

During ancient times, the dam is built solely for water supply however as humans evolves, the function of the dam also increased in order to fulfil human needs. As time passing, a problem has aroused which causing a lot of difficulties at the dam. The problem is caused by the sediment. Sedimentation will affect the dam in various things such as the safety of dams and reduces energy production, storage, discharge capacity and flood attenuation capabilities. The purpose of this research is to study the movement of the sediment transportation at the TNB hydropower station at Chenderoh Dam. The scaled down model is constructed using the SolidWorks and then it is fabricated to the physical model. The simulation of 3D model is carried out using ANSYS Fluid Structural Interaction. The formulation used is Discrete Particle Method (DPM), Discrete Element Method (DEM) and Navier-Stokes respectively. Particle image velocimetry experiment will also be conducted to verify the simulation results. Finally, the results such as velocity and flow direction are compared, acknowledging the great similarity between numerical simulation and experimental test. Also, in this study, the chemical properties of the sediment and its size are found. Moreover, the scouring rate also being discussed in this research. The highest percentage error between simulation and PIV is 4.89%. Additionally, the highest scouring rate is 4.20E-9 kg/s while highest deposition rate is 2.00E-6 kg/s. According to the findings, the period for a maintenance needs to be done is every 8.9 years. These results will serve as a basis to improve the sediment transportation at Chenderoh Dam in the future.

CHAPTER 1 : INTRODUCTION

In ancient times, dams were built to fulfil the single purpose of water supply or irrigation. As civilizations and countries developed, multipurpose dams are built, and they are very useful project because the population receives domestic and economic benefits from a single investment. For example, hydroelectric power is a major supply of electricity in the world. Many countries have rivers with sufficient water flow that can be dammed to generate electricity. The reservoir water is stored at a higher level than the turbines, which are housed in a power station. Sometimes, the power station is directly in front of a dam, and pipes through the dam feed water directly to the turbines. In other cases, the power station is some distance downhill from the reservoir, and the water is fed to it through long pipes or tunnels called penstocks.

In other situation, the dams play a role to control and stabilize water flow often used for agricultural purposes and irrigation. The irrigation water will be stored in the reservoir during the rainy season and then in the drier season, it can be released from the reservoir and distributed throughout the land.

Chenderoh Dam is the oldest hydroelectric dam and power station in Malaysia. It is located in Tasik Chenderoh, near Kuala Kangsar, Perak. The dam was constructed on the early 1920s by the British Federated Malay States administration. The power station is a hydroelectric power station, using 4 turbines of 10.7 MW and one of 8.4 MW, totaling 40.5 MW installed capacity. The station is operated by Tenaga Nasional. The dam cost about £3.5 million and was built by Messrs. Armstrong, Whitworth and Co. with half of its cost provided by the British Government under the credit scheme, and the British Government was represented on the board of Perak Hydro-Electric Company.

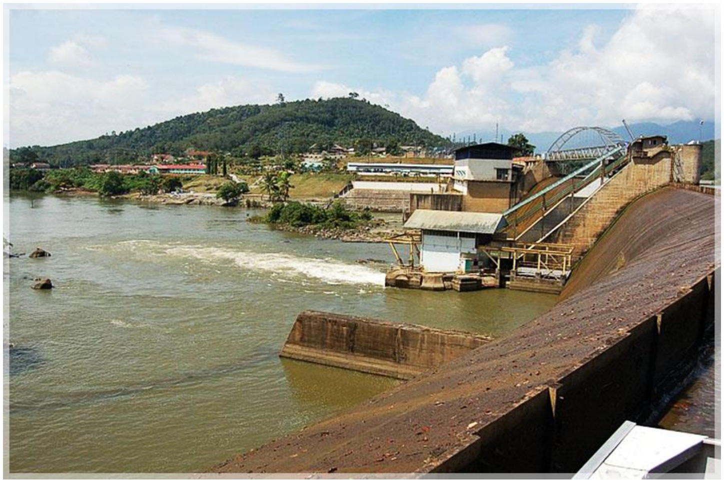


Figure 1. 1*: Chenderoh dam*

1.1 Research Background

Sediment refers to the composition of 2 materials, organic and inorganic, that can be carried away by water or wind. The term is also being used to indicate soil-based, mineral matter (e.g. clay, silt and sand), decomposing organic substances and inorganic biogenic material are also considered sediment. Most mineral sediment comes from erosion and weathering, while typically debris and decomposing material such as algae is called as organic sediment. The processes of erosion, transport, and deposition of sediment, collectively termed as sedimentation, are natural processes and have been occurring throughout the geologic time.

In an aquatic environment, sediment is divided into 2 categories such as suspended (floating in the water column) or bedded (settled on the bottom of a body of water).

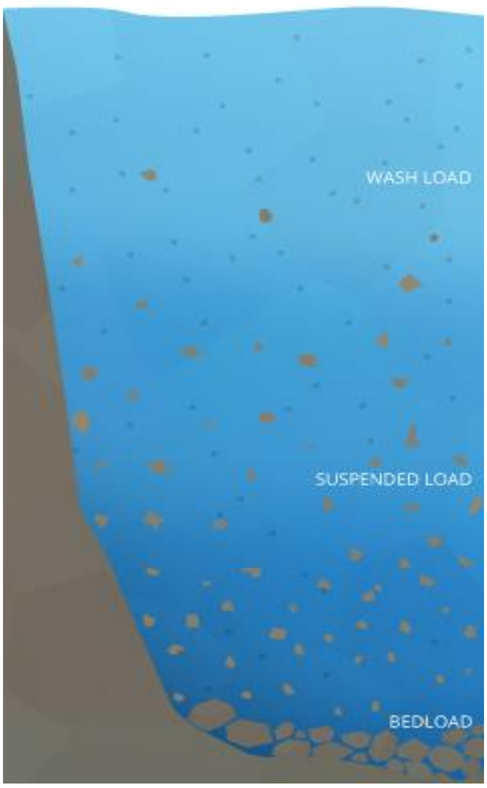


Figure 1. 2 *: Suspended and Bedded Sediments*

Sediment transport is a transportation movement of organic and inorganic particles by water. In general, more sediment will be conveyed if there is greater flow. As they move downstream, water flow can be strong enough to suspend particles in the water column, or simply push them along the bottom of a waterway. Transported sediment may contain mineral matter, chemicals and pollutants, and organic material.

Sedimentation affects the safety of dams and reduces energy production, storage, discharge capacity and flood attenuation capabilities. The major properties of sediment and its transport are the following: the particle size, shape, density, sedimentation velocity, porosity and concentration. A key concern in many dam removal proposals is the routing of sediment stored behind reservoirs, including downstream channel response and release of contaminated sediments (e.g., Randle, 2003). No studies have been completed to document and quantify channel response to the removal of large dams (Graf, 1996), although field observations following the removal of small dams have intensified in recent years (e.g., Pizzuto, 2002; Doyle et al., 2003).

This research is important due to several problems faced by the Chenderoh Dam today where the government need to spend more than a million per session to remove the sediment that deposited at the bottom of the upstream dam. Sediment deposition causes loss of water storage in reservoir which reduce the flexibility in generation and affects the reliability of water supply. Around the world, it is about 5% to 1% of the total volume of 6,800 km^3 of water stored in reservoirs lost annually as a result of sedimentation.

By trapping sediment in reservoirs, dams interfere with the continuity of sediment transport through rivers, resulting in loss of reservoir storage and giving threats to aquatic habitats. In the past, there have been various researchers that simulated the flow of water in dam, for instances smoothed particle hydrodynamics (SPH) model, MIKE 11 1-D hydrodynamic model and fluid/structure interaction (FSI). Among these approaches, the FSI simulation has proven to be more valid as it able to capture both aspects of fluid flow and structural deformation in the modelling.

To simulate the particle of sediment deposition, Discrete Phase Model (DPM) and Discrete Element Method (DEM) will be used. A discrete phase model should be set when the flow of a discrete phase (particles) with a continuum is modelled like this problem. The forces acting on particles are categorized in five factions such as gravity, drag, lift, pressure gradient and virtual mass. While, DEM is a particle-scale numerical method for modelling the bulk behaviour of granular materials and many geomaterials such as coal, ores, soil, rocks, aggregates, pellets, tablets and powders. This method has been applied to simulate and analyze flow behaviour in a wide range of disciplines such as pharmaceutical and process engineering, mechanical engineering, materials science, agricultural engineering and more.

1.2 Problem Statement

At Chenderoh Dam, the sedimentation gives a serious threat to the sustainability of hydropower which can cause serious damage like dam fails. During the events of dam failure, an uncontrolled release of huge volume water together with immense potential energy stored in it will strike the immediate downstream areas, endangering lives, damaging properties along its path and eventually result in widespread flooding.

In addition to these property damages, ecosystems and habitats are destroyed because of waters flooding them. Furthermore, sediment also can damage turbines and other mechanical machinery through the erosion leading to surface irregularities and more severe material damage. Therefore, careful planning is required to choose the best method used to remove the sedimentation.

1.3 Objectives

- To identify the properties of particle in water river at Chenderoh Dam.
- To simulate the sediment transportation at Chenderoh Dam by using Discrete Phase Model (DPM) and Discrete Element Method (DEM).
- To validate the simulation results by conducting Particle Image Velocimetric (PIV).

1.4 Scope of Project

Basically, the scope of work includes the design phase, simulation phase and experiment. For the design phase, the scaled down (1:40) Chenderoh Dam model is established using SolidWorks. Next, the created geometries are used in the subsequent simulation phase. The simulation is carried out using ANSYS Fluid Structure Interaction (FSI) since multiphysics problem is involved. Finally, PIV experiment is conducted to compare the results with the simulation for validation purpose. The physical model used in both simulation and experiment are similar to the actual Chenderoh Dam to ensure that the results obtained are applicable to the real world.

CHAPTER 2: LITERATURE REVIEW

2.1 Modelling Sediment Transport

In line with [Cui and Wilcox, 2008], previous simulations have provided a basis for modelling sediment transport because reservoir sediment deposits behave as large sediment once dams are removed. A sediment pulse model of Cui and Parker is applied successfully to simulate the evolution of a large landslide in the Navarro River, California. The first adaptation of model Cui and Parker to dam removal were applied to a potential removal of two dams in Oregon, Soda Spring Dam and Marmot Dam. This project presents the Marmot Dam removal modelling effort as a case study of the application of sediment-transport modelling to dam removal. Then, [Cui et al., 2008] further developed the Dam Removal Express Assessment Models (DREAM). For fine sediment, DREAM-1 was used for simulation and DREAM-2 was used for simulation with top layer of the reservoir sediment composed of gravel and coarser. Sediment transport models have also been applied to dam removal evaluations. HEC-6 of U.S Army Corps of Engineers was used to simulate sediment released associated with proposed dam removals on Elwha River, Washington. However, the models were usually not capable of simulating the upstream and downstream reaches of a dam simultaneously.

The main challenge based on [Cui and Wilcox, 2008] paper in any dam -removal modelling exercise is to simultaneously model the sediment transport processes in upstream of the dam and downstream of the dam. Very steep slopes in the important transition area between reaches upstream and downstream of the dam can produce transient flow condition which potentially resulting in numerical instabilities. Therefore, various techniques can be used in coupled modelling of upstream and downstream reaches. For instance, flow near the dam site can be simulated using a fully coupled model that that retains the unsteady terms in St. Venant shallow water equations. By applying a fully coupled model, application of artificial viscosity terms. Even the artificial viscosity terms were used, there will still be high-frequency oscillation in the solution for water depth and flow velocity which may result in instability in the solution for bed elevation.

To select appropriate sediment transport equation, we need to consider many aspects. For example, complex nature of reservoir sediment deposits can be a problem to sediment-transport modelling. Its size of distribution of reservoir sediments is wide ranging from boulders to clay. So, the modeller must select sediment transport equation and make other assumption that are convenient to the particular reservoir that is on research. Based on the paper of [Cui and

Wilcox, 2008], there still no sediment transport equations were found to handle mixtures of coarse and fine sediment. [Wilcock and Crowe, 2003] introduced an equation of sediment transport that provides first attempt to calculate transport of coarse and fine sediment simultaneously while accounting for the grain size distribution of the coarse sediment. This equation computes gravel-transport rate and sand transport rate. For gravel-transport rate, it calculates by size fractions and for sand transport, it is based on known shear stress and surface grain-size distribution. This modelling equation then was adopted for Marmot Dam removal study. It is based on the two assumptions. Firstly, the coarse sediment is transported primarily as bed load during high flow events, when fine sediment is transported primarily as suspended load. Secondly, most fine sediment is transported during the intermediate flow events, when coarse sediment transport is limited.

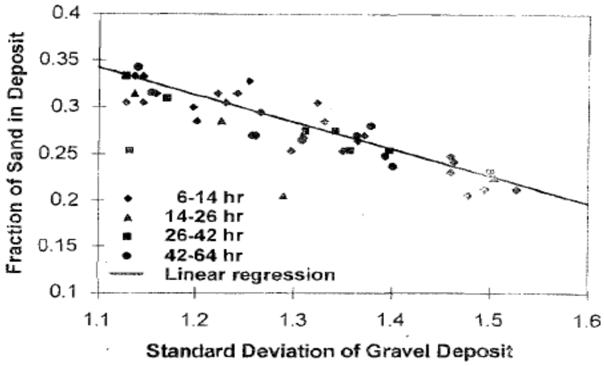


Figure 2. 1*: Fraction of sand in deposit vs standard deviation of gravel deposit*

According to [Kondolf et al., 2014], to allow sediment to be transported through the reservoir as rapidly as possible while minimizing sedimentation, drawdown routing or sluicing is introduced which involves discharging high flows through the dam during periods of high inflows to the reservoir. Sluicing is performed as shown in figure below by lowering the reservoir pool prior to high-discharge sediment-laden floods. Benefit from this method is that the deposition in the reservoir is minimized. Finer sediments are more effectively transported compared to coarse sediments.

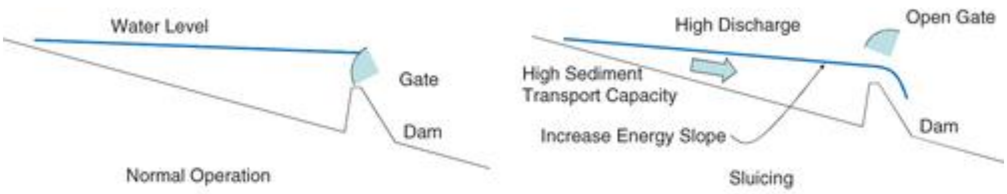


Figure 2. 2 *: Sluicing*

For case study of sedimentation and flushing into the reservoir Paute-Cardenillo in Ecuador by paper [Luis G. Castillo, Manuel A. Álvarez, José Mª Carrillo, 2014], the calculation of the flow characteristics depends mainly on the resistance coefficient, hydraulic radius and longitudinal slope. According to methodology applied in [Castillo et al, 2009] four aspects were checked to determine hydraulic characteristics of the flow such as macro roughness, bed form resistance, hyper concentrated flow, and bed armoring phenomenon. Ten formulae were applied to estimate the roughness coefficient: [Strickler, 1923; Limerinos, 1970; Jarret, 1984; Bathurst, 1984; van Rijn, 1987; Fuentes and Aguirre-Pe, 1991; García-Flores, 1996; Grant, 1997; Fuentes and Aguirre-Pe, 2000; and Bathurst, 2002]. These formulae were calculated by coupling iteratively the characteristics of hydraulic with the sediment transport.

For estimating of sediment transport, [Luis G. Castillo, Manuel A. Álvarez, José Mª Carrillo, 2014] used fourteen formulations of sediment transport capacity such as [Meyer-Peter and Müller, 1948; Einstein and Brown, 1950; Einstein and Barbarrosa, 1952; Colby, 1964; Engelund and Hansen, 1967; Yang, C.T., 1976; Parker *et al.*, 1982; Smart and Jaeggi, 1983; Mizuyama and Shimohigashi, 1985; van Rijn, 1987; Bathurst *et al.*, 1987; Ackers and White, 1990; Aguirre-Pe *et al.*, 2000; and Yang, S., 2005]. Iber two-dimensional simulation was used for flushing simulation because one-directional model was unable to reproduce the regressive erosion of sediment in the reservoir. Iber can be divided in three parts: hydrodynamic, turbulence and sediment transport. Triangular or quadrilateral elements in an unstructured mesh and finite volume scheme was used for the program. The hydrodynamic module solves shallow water equations using 2-D Saint-Venant equations. The sediment transport module solves the transport equations by the Meyer-Peter & Müller and van Rijn expressions.

In contrast to sluicing, [Kondolf et al., 2014] state that flushing focuses on scouring and re-suspending deposited sediment and transporting it downstream. According to [White, 2001], flushing is best adapted to small reservoirs and on rivers with strongly seasonal flow patterns. In addition, [Morris and Fan, 1998] proposed that flushing differs from sluicing in two key respects. Firstly, flushing focuses on the removal of previously deposited sediments, instead of passing incoming sediments through the dam. Second, the timing of sediment release to the downstream channel may be different from that of the sediment inflow into the reservoir.

Flushing has been successfully implemented in many dams around the world, such as Unazuki and Dashidaira dams in Japan [Kokubo *et al.*, 1997; Liu et al., 2004; Sumi and Kanazawa, 2006], Sanmenxia dam in China [Wan, 1986; Wang *et al.*, 2005], Cachi Dam in

Costa Rica [Jansson and Erlingsson, 2000], and Genissiat Dam on the Rhône River in France [*Thareau et al*., 2006], and recommended as the only sediment management measure feasible in terms of public acceptance and cost for Gavins Point dam on the Missouri River [US Army Corps of Engineers, 2002].

Based on Sediment problems and strategies for their management book by [Cheng Liu, Desmond E. Walling, Manfred Spreafico, Jayakumar Ramasamy, Hans Dencker Thulstrup, Anil Mishra et al, 2017], the alternative for transporting the sediment is by underwater dredging or dry excavation of the deposited material. In certain area like the Roseires Reservoir in the Nile River Basin, this method is necessary because flushing and sluicing are insufficient to control sedimentation. Another technique for managing the sedimentation is to adopt methods that prevent or reduce the settling and deposition of fine sediments such as exploiting and controlling turbidity currents.

While for modelling, there are some modelling that researcher used to simulate the water flow such as smoothed particle hydrodynamics (SPH) model, MIKE 11 1-D hydrodynamic model and fluid/structure interaction (FSI).

In consonance with [Fourtakas and Rogers, 2016], the basic principle of the SPH formulation is the integral representation of a function f which may represent a numerical or physical variable defined over a domain of interest Ω at a point $\mathbf{x}$. The multi-phase model focuses on liquid-sediment flows and more specifically the scouring and resuspension of the solid phase by liquid induced rapid flows. The modelling technique is choose based on the explicit treatment of the liquid and solid phase using a Newtonian and a non-Newtonian constitutive model respectively that is supplemented by the Drucker-Prager yield criterion to predict the yielding characteristics of the sediment surface and a suspension model based on the volumetric concentration of the sediment.

Definition of fluid structure interaction (FSI) is the interaction of some deformable structure with a surrounding internal fluid flow. One of the most important and challenging multi-physics problems is the analysis of corresponding coupled system which are aimed to be solved by numerical simulations. Solutions of such problems are normally required in various applications, ranging from small-scale micro pumps over blood flow in arteries, to biomechanical systems, break systems (optimization and control), objects in a wind tunnels up to unique buildings [Rugonyi and Bathe. et al., 2001]. Thus, more research and development on finite element methods (FEM) for solution of FSI problems is apparently important. To the best knowledge of the authors, research was rarely being conducted to determine the sediment transport in water flow. Therefore, the current study is a worthy research investment that can offer a new perspective to FSI simulation of sediment transport at dams.

2.2 Simulation of granular materials

In 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. The previous effort in this study can be divided into two main methods which are particle-based methods and mesh-based methods.

A simulation of granular materials, such as sand and grains, has been presented by [Bell et al., 2005] based on theoretical and experimental results. In their concept, the granular materials are modelled with discrete elements represent by particles. One of the major advantages of this method is that dynamic phenomena, like splashes and avalanches, can be generated by particles' interaction with high physical accuracy [12]. This simulation technique is based on Molecular Dynamics methods 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 Bridson, 2005] introduce a combination of particle-in-cell (PIC) and fluid-implicit-particle (FLIP) methods to simulate sand as fluid. [Alduan et al., 2009] 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].

[Kloss, Goniva, Aichinger and Pirker, 2009] in their study revealed that DEM captures the physics of granular materials best but is computationally time consuming [13]. Therefore, a Discrete Phase Model (DPM) is needed to complement with DEM for disperse granular flow in order to accelerate the overall simulation. This study seeks to analyse the effect of complementing DEM and DPM in CFD method. The Discrete Element Method was invented by [Cundall and Strack, 1979]. In the frame of the DEM, all particles in the computational domain are tracked in a Lagrangian way, explicitly solving each particle's trajectory, based on corresponding momentum balances for translational and angular accelerations [13]. The

Discrete Element Method 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 [12]. The literature of [e.g. Campbell, 1990; Zhou et al., 1999; Mattutis et al., 2000; Bertrand et al., 2005] will explain more details on the contact physics and implementational issues.

There are limited studies in DEM method due to the issue of handling a ton of particles. In most cases, the DEM is not used in real time application. However, [Maknickas and Kaceniauskas, 2006] have proposed a parallelisation 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.

2.3 Scanning Electron Microscopic (SEM) and EDX

The literature of [Kim, Park, & Kim, 2014], 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. This study is supported by the findings of [DeJong, Mortensen, Martinez, & Nelson, 2010] literature where the results from SEM and EDX provide clear images of the particles and quantitative analysis of the specimens.

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 [Zhu, Li, Zhang, Song, and Zheng, 2017]. This is supported by study of [Matos, Silva, Soares, Salta, Mirão, and Candeias, 2010] where it explains that microscopy is the only technique capable to clearly identify the features associated with DEF in concrete.

2.4 Scouring or Deposition rate

A study of scour by [Castillo and Carrillo, 2016], the similar results have been obtained by solving the problem from three different perspectives: empirical formulations, pressure fluctuations-erodibility index and CFD simulations. Another study by [Kitamura, & Takagi, 2016], uses field observations, mathematical model tests and several hydraulic scale models. Also, 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. However, in the study by [Comiti, Lenzi, & Mao, 2010], the empirical and semi-empirical equations presented in this paper are shown as the most reliable tools to predict the maximum scour depth.

2.5 Validation using PIV

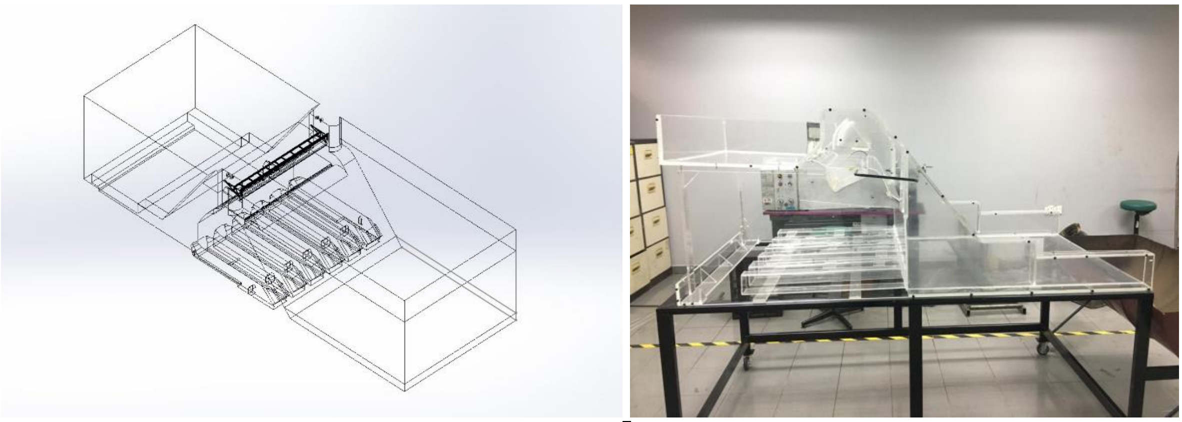
The proposed study by [X Xie, Le Men, Dietrich, Schmitz, and Fillaudeau, 2018] proved that the capabilities of PIV indicates velocity fields and profiles were highly organized although velocity of rotating impeller was high. In another study by [Peltier, Dewals, Archambeau, Pirotton, and Erpicum, 2015], the velocity fields were measured using Large Scale Particle Image Velocimetry (LSPIV) and their findings showed that relative flow velocity is slightly higher for greater spillway.

Another study by [Abas, Jamil, Rozainy, Zainol, Adlan, and Keong, 2017] also shows that the PIV experimental data in the flow pattern can be used to predict the result for their study and also validate their findings. This study is supported by [Kantoush, Sumi, and Murasaki, 2011] findings where they used Large Scale Particle Image Velocimetry (LSPIV) to evaluate the flow pattern and validate it with the simulation. [Azman, Zawawi, Hassan, Abas, Razak, Mazlan, and Rozainy, 2018] found that the PIV can compute the flow patterns, velocity and aeration efficiency performance.

CHAPTER 3 : METHODOLOGY

3.1 Establishment of CAD Model

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 original dam at Chenderoh. 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 3. 1** below.



(a) (b)

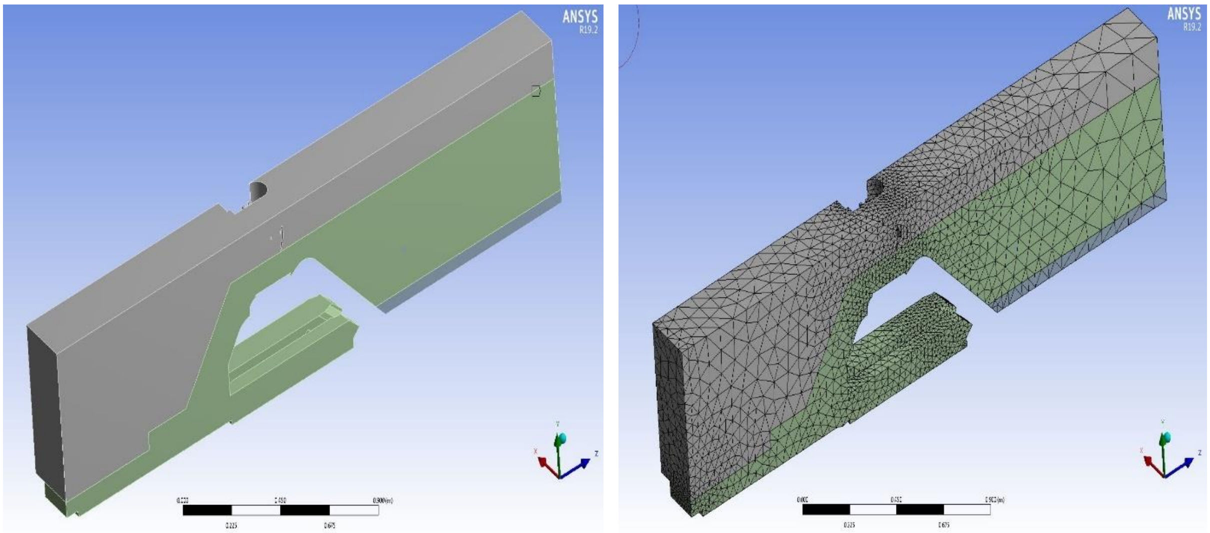
Figure 3. 1 *: (a) CAD model (b) Fabrication of the Model*

3.2 Simulation Using ANSYS Fluid Structure Interaction (FSI)

In computational fluid simulation, ANSYS software is used to simulate the transportation of the sediment in the dam. Fluid-structure interaction (FSI) is a coupling of multiphysics between the laws that describe fluid dynamics and structural mechanics. This happening is characterized by interactions between a deformable or moving structure and a surrounding or internal fluid flow.

The environment of conventional reflow process is replicated in Ansys FLUENT using two-way interactions of multiphase VOF and DPM model. A scaled down 3-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. 2**. The mesh developed for the current model is based on tetrahedrons mesh.

The solver used to solve coupling of both pressure and velocity in this model is Semi-Implicit Method (SIMPLE) algorithm scheme. This numerical solver is used to obtain high accuracy result.



(a) (b)

Details of "Mesh"	
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Growth Rate	Default (1.2)
Max Size	0.32 m
Capture Curvature	Yes
Curvature Min Size	2.e-002 m
Curvature Normal Angle	Default (18.0°)
Capture Proximity	No
Bounding Box Diagonal	2.8941 m
Average Surface Area	2.6451e-002 m^2
Minimum Edge Length	2.133e-006 m
Quality	
Check Mesh Quality	Yes, Errors
Smoothing	High
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
View Advanced Options	No
Assembly Meshing	
Method	Tetrahedrons
Feature Capture	Program Controlled
Tessellation Refinement	Program Controlled
Intersection Feature Creation	Program Controlled
Advanced	
Number of CPUs for Parallel...	Program Controlled
Statistics	
Nodes	12653
Elements	60382

Figure 3. 2 *: Schematic diagram of the dam (a), meshing (b), and details of mesh*

Tetrahedral mesh with their mesh elements being optimized were adopted in present simulation as shown as **Figure 6**. Such optimized mesh enables both low computational cost at reasonably good numerical accuracy to be achieved.

The model is divided into three parts which are air, water and sediment. The zones of the BC in the FLUENT set-up are inlet, outlet and the rest are set as wall (**Figure 3. 3**). For the mixture phase of the inlet, velocity inlet BC 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; while no-slip wall condition being imposed such that the wall-fluid velocity is 0 m/s. Moreover, the pressure at the inlet and outlet equal the atmospheric pressure which is 0 Pa (gauge). For particle of sediment and water flow, the equation used is Discrete Phase Model, Discrete Element Method and Navier-Stokes respectively.

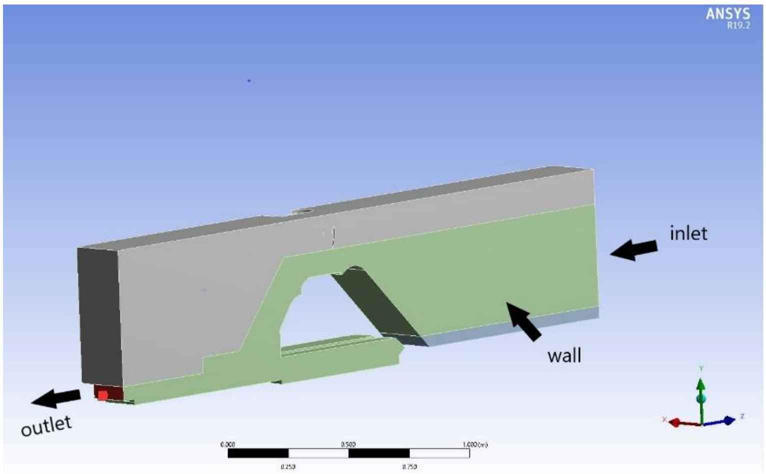


Figure 3. 3 *: Boundary condition*

3.3 Governing Equations

The numerical model used in this study is based on Navier-Stokes equation that involve conservation of mass and momentum:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = 0 \quad (3.1)$$

Energy equation:

$$\rho C_p\left(\frac{\partial T}{\partial t} + u\nabla T\right) = \nabla(k\nabla T) + \Phi \quad (3.2)$$

Momentum equation:

$$\frac{\partial(\rho u)}{\partial t} + \nabla(\rho u u) = -\nabla P + \nabla \tau + \rho g \tag{3.3}$$

in which, ρ denotes the density of the fluid, **u** is the velocity, τ is the shear stress and gravity, **g** = -9.81 m/s.

The model is based on two phase interactions of water and air. Both phases are distinguished by the volume of fraction (VOF) in the range 0 to 1 with $f = 1$ indicating the presence of water as described below,

VOF transport equation:

$$\frac{\partial \rho}{\partial t} f + u \nabla f = 0 \tag{3.4}$$

The trajectory and tracking of the particles in the fluid are associated with the mass and other forces exerted on each of the particles as given by:

Particle force balance:

$$\frac{\partial u_p}{\partial t} = F_D(u - u_p) + g_x \frac{(\rho_p - \rho)}{\rho_p} + F_x \tag{3.5}$$

where $F_D (u - u_p)$ is the drag force associated with the velocity of fluid and particles, μ is the molecular viscosity of the fluid, ρ_p is particle density and d_p is the particle diameter.

Additional force, F_x is related to the mass, acceleration and pressure gradient in the fluid based on the consideration that $\rho > \rho_p$.

$$F_x = \frac{\rho}{\rho_p} u_p \left(\frac{\partial u}{\partial x}\right) \tag{3.6}$$

For multiphase flows, you can optionally include the “virtual mass effect” that occurs when a secondary phase $\boldsymbol{\rho}$ accelerates relative to the primary phase $\boldsymbol{q}$. The inertia of the primary-phase mass encountered by the accelerating particles (or droplets or bubbles) exerts a “virtual mass force” on the particles. The virtual mass force is defined as:

$$\overline{F}_{vm} = 0.5\alpha_p\rho_q\left(\frac{d_q\overline{v}_q}{dt} - \frac{d_p\overline{v}_p}{dt}\right) \tag{3.7}$$

The term $\frac{d_q}{dt}$ denotes the phase material time derivative of the form.

$$\frac{d_q(\phi)}{dt} = \frac{\partial(\phi)}{\partial t} + \left(\overline{v}_q \cdot \nabla\right)\phi \tag{3.8}$$

The virtual mass $\vec{F}_{vm}$ force will be added to the right-hand side of the momentum equation for both phases ($\overline{F}_{vm,q} = -\overline{F}_{vm,p}$).

The virtual mass effect is significant when the secondary phase density is much smaller than the primary phase density (for example, for a transient bubble column). The sediment is expected to move along with the water which show two-way interaction of the multiphase-DPM.

3.4 Scanning Electron Microscopic

3.4.1 Overview

A scanning electron microscope, or SEM, is a powerful microscope that uses electrons to form an image. The images taken can be magnified using the SEM which cannot be achieve using traditional microscopes. Typical SEM can reach magnifications of more than 30,000X while modern light microscope only can be magnified up to 1,000X. The result images will be in form of black and white because the SEM doesn't use light to create images.

Conductive samples are loaded onto the SEM's sample stage. The user will proceed to align the electron gun in the system to the proper location once the sample chamber reaches vacuum. The electron gun shoots out a beam of high-energy electrons, which travel through a combination of lenses and apertures and eventually hit the sample. As the electron gun continues to shoot electrons at a precise position on the sample, secondary electrons will bounce off of the sample [10]. The detector will identify these secondary electrons then the signal found from the them is amplified and sent to the monitor, creating a 3D image.

3.4.2 Principle

Electrons are generated by heating by the electron gun, which acts like a cathode. These electrons are propelled towards the anode, in the same direction as the sample, due to a strong electric field. Objective lens, which is calibrated by the user to a fixed position on the sample, will be entered by the beam of electrons after it condensed. (**Figure 3. 4)**

Once the electrons strike the conductive sample, two things can happen. First, the primary electrons that hit the sample will tunnel through it to a depth which is dependent on the energy level of those electrons. Then, both secondary and backscattered electrons will hit the sample and rebound outwards from it. These reflected electrons are then measured either by the secondary electron (SE) or backscattered (BS) detector [10]. An image of the sample is formed on the screen after signal processing takes place.

In SE mode, positive bias will attract the secondary electrons on the front of detector due to their low energy. The signal intensity is varied depending on the angle of the sample. Therefore, SE mode provides highly topographical images. On the other hand, in BS mode, the direction of electrons is almost directly opposite of the e-beam direction and the detection intensity is proportional to the atomic number of the sample. Therefore, it is less topographical, but useful for compositional images. BS mode is also less affected by the charging effect on the sample, which is beneficial for non-conductive samples.

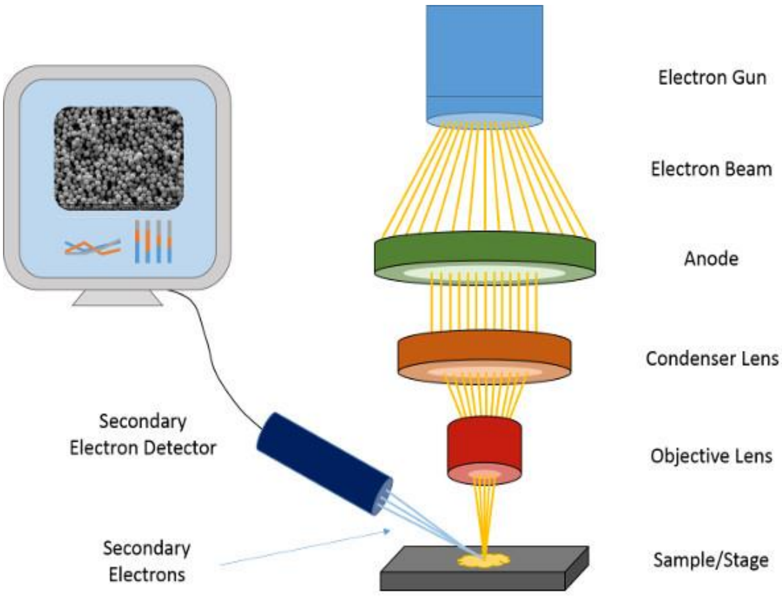


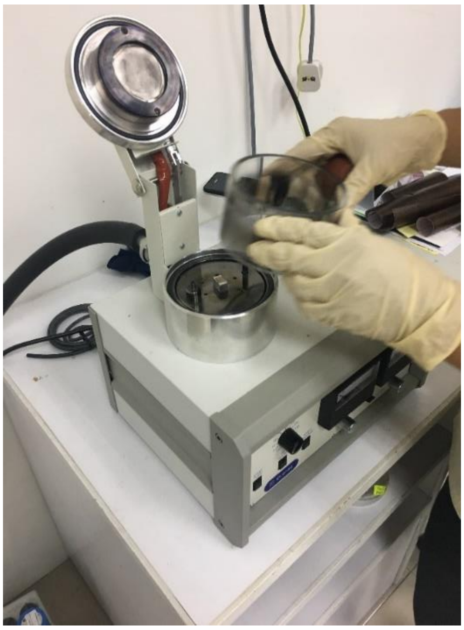
Figure 3. 4 *: Schematic diagram of SEM*

3.4.3 Procedures

3.4.3.1 Preparing the sample.

Sample was placed onto sample stub. If necessary, carbon tape may be used to adhesively bond the sample to the stub.	 **Figure 3. 5** *: Place the sample onto the sample stub*
The sample stub was blown using blower to remove the excessive and unwanted particles.	 **Figure 3. 6** *: Blowing excessive and unwanted particles*

<table>
<tr>
<td>The sample was placed into a gold sputtering system. Using a mini-gold sputter, sputter gold for like 30 s at ~ 70 mTorr pressure. The geometry of the sample will determine the difference gold layer thickness. More rough or porous surface requires a longer sputtering time. It needs to be coated with AU element (gold). This was due to its non-conductive nature where its surface acts as an electron trap. This accumulation of electrons on the surface was called ‘charging’ and creates the extra-white regions on the sample which can influence the image information [11]. The charging electrons will be removed from the material through conductive coating material which acts as a channel.</td>
<td>
Figure 3. 7 : Sputtering machine</td>
</tr>
</table>

Stub was removed from gold sputtering system.	 **Figure 3. 8** *: Removing the stub from sputter machine*

3.4.3.2 Sample Insertion and SEM Startup

i. SEM chamber was vented, allowing the chamber to reach nominal pressure.

ii. The SEM sample compartment was opened and the sample stage was taken out.

iii. The sample stub containing the sample was entered onto the stage. Then, the stub was tightened into place.

iv. The sample stage was put into sample chamber then the sample compartment was closed.

v. Pumps were turned on and the system was allowed to reach vacuum. The system will notify the user when the action was completed.

vi. The SEM software was opened. Desired operating voltage was selected ranging from 1–30 kV. Higher operating voltage gives better image contrast however if charges accumulate in the sample, it can yield lower resolution.

Figure 3. 9 : *SEM chamber*

3.4.3.3 Capturing the SEM Image

i. The key icon was clicked to begin 'Auto Focus' in the SEM. This will acquire a focused image of the sample to use as a starting point.

ii. The magnification was made sure to be set to the minimum zoom level of 50X.

iii. The 'fast scan' mode was selected.

iv. The focus was adjusted in coarse mode until a rough focus was acquired.

v. The stage was manually adjusted using the exterior knobs so that the region of interest was visible on the display.

vi. The magnification level was increased until the desired feature was observed. Then, the coarse focusing knob was adjusted to roughly focus the image at this magnification. Next, the focus was improved using the fine focusing knob to get a focused image at the desired magnification level. This step needs to be repeated whenever the magnification level was increased.

vii. Once the desired magnification was reached, the fine focusing knob was adjusted to improve clarity.

viii. The magnification was increased close to the maximum level, and then the image was focused using the fine focus knob in order to optimize image clarity. If a clear image cannot be obtained, the stigmation should be adjusted in both the x and y direction. The focus needs to be kept adjusted and stigmations until the clearest image was obtained at the exaggerated magnification level.

ix. Once a quality image of the sample was obtained, go back to the desired magnification level. The image can be taken by pressing the photo button in either ‘fast photo’ or ‘slow photo’ mode. The ‘slow photo’ mode gives high resolution and better quality of the image.

3.4.3.4 Making Measurements Using the SEM Software

i. In the ‘Panels’ dropdown list, ‘M. Tools’ was selected.
ii. Various measurements such as length, area, and angle can be measured directly in the SEM software so to perform one of these measurements, the desired icon in the M. Tools window was selected.
iii. Scroll to the measurement site on the SEM image. Measurements were done by clicking on the image to create points of reference that will be analyzed by the software. Data points measured can be inserted directly onto the image if desired by the user.
iv. Images are then saved to the computer.

Figure 3. 10 *: Analyzing the sample using SEM software*

3.5 PIV formulation

Particle image velocimetry (PIV) is an optical method that can be used to determine the instantaneous vector measurement throughout the cross-sectional view. The motion is followed via the use of small tracer particles (Polyamid Seeding Particles). Based on the positions of these tracer particle at two different instances of time can we obtained the particle displacement to infer the flow velocity field. Velocity vector of the fluid through the tracer particles are computed based on the movement of tracer particle between two light pulses:

$$V = \frac{\Delta x}{\Delta t} \tag{3.9}$$

The primary source of measurement error relies on the influence of gravitational forces, when the density of the tracer particles is different to the density, ρ of work fluid.

$$V_g = {d_p}^2 \frac{(\rho_p - \rho)}{18\mu} g \tag{3.10}$$

The velocity lag, of a particle in a continuously acceleration fluid is given by:

$$\vec{V_s} = \vec{V_p} - \vec{V} = {d_p}^2 \frac{(\rho_p - \rho)}{18\mu} g \tag{3.11}$$

$$V_p(t) = V(1 - \exp\left(-\frac{t}{\tau_s}\right)) \tag{3.12}$$

$$\tau_s = \ d_p \frac{\rho_p}{18\mu} \tag{3.13}$$

This technique consists of the measurement of the fluid displacement, Δx over a given time interval, Δt. The LED light will illuminate the tracer particles by creating a thin laser light sheet. Then subsequently, the image will be captured using a camera specifically at the target area.

3.5.1 Experiment setup

Figure 3. 12 represents the flow of general experimental setup for conducting the validation process on dam's physical model. Several crucial materials and instruments would have to be prepared and then set up properly before the carrying out the experiment. Camera video is placed perpendicularly to the laser to record the flow of water from the side.

Figure 3. 11 *: The arrangement of laser and camera for the experiment.*

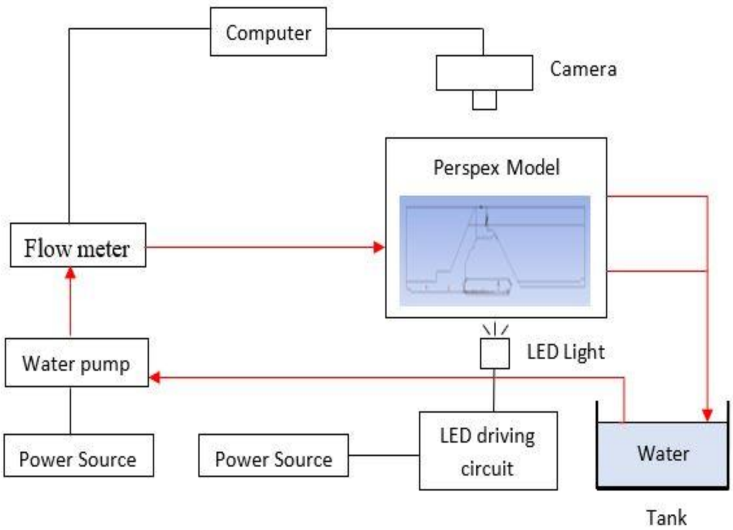


Figure 3. 12 *: Schematic overview of the experimental setup*