A FLOW PATTERN STUDY OF TEMENGGOR DAM HYDRAULIC PHYSICAL MODEL

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By

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Finally, I hope that this dissertation will benefit and assist anyone who is interested in the field of hydraulics especially, studying the flow pattern of hydraulic physical model.

ABSTRAK

Mutakhir ini, kelestarian pengoperasian empangan hidroelektrik telah dipersoalkan kerana ketahanan dan kecekapannya. Faktor-faktor seperti pemendapan, hakisan dan pembentukan pusaran di empangan telah memberi kesan buruk untuk empangan beroperasi pada tahap yang optimum. Corak aliran yang seragam dan stabil di sepanjang hulu empangan adalah penting dalam memastikan kelestarian empangan terjamin kerana kesan yang minimum daripada hakisan, pemendapan dan pusaran. Kajian ini telah menilai potensi terhasilnya pemendapan, hakisan dan pembentukan pusaran di Empangan Temenggor melalui model fizikal hidraulik berskala 1:100. Terdapat empat kes telah diuji bagi menentukan hakisan, pemandapan dan pusaran yang terhasil iaitu Kes 1 (kedudukan salur masuk air di tengah dan pada peringkat 0.38m), Kes 2 (kedudukan salur masuk air di tengah dan pada peringkat 0.34m), Kes 3 (kedudukan salur masuk air di sisi dan pada peringkat 0.38m) dan Kes 4 (kedudukan salur masuk air di sisi dan pada peringkat 0.34m). Berdasarkan Kes 3, julat halaju aliran yang telah diperolehi ialah 0.3 – 2.1 m/s pada 20% dari permukaan air, membawa kepada hakisan di sepanjang tebing empangan dan pemendapan yang tertumpu pada bahagian sisi empangan yang telah mengancam kestabilan empangan akibat beban tertumpu oleh endapan. Pusaran jenis 5 – 6 telah dikenal pasti dalam tempoh 15-30s yang memerlukan langkah pencegahan segera bagi memastikan kelestarian Empangan Temenggor terjamin. Hasil kajian mendapati bahawa corak aliran di hulu Empangan Temenggor telah dipengaruhi oleh kedudukan salur masuk air dari hulu empangan, kadar aliran air dan kedalaman dari paras air.

ABSTRACT

Recently, the sustainability of hydroelectric dams has been questioned due to their reliability and efficiency. Factors such as sedimentation, erosion and vortex formation at the dams have adversely impacted the sustainability of the dam to function optimally. A stable and uniform flow pattern at the dam's upstream is important to ensure the sustainability of dam is preserved due to minimal impacts of erosion, sedimentation and vortex. The study had assessed the potential of sedimentation, erosion and vortex formation at Temenggor Dam, based on the flow pattern formed via hydraulic physical model with a scale of 1:100. There are four cases have been tested which are Case 1 (the position of water inlet at the middle and at stage of 0.38m), Case 2 (the position of water inlet at the middle and at stage 0.34m), Case 3 (the position of water inlet at the side and at stage of 0.38m) and Case 4 (the position of water inlet at side and at stage 0.34m). Based on Case 3, the range of flow velocities obtained was 0.3 – 2.1 m/s at 20% from water surface, leading to erosion which occurred alongside the bank of the dam and sedimentation which focussed on the side of the dam that threatened the stability of the dam due to the concentrated load of sediment. Vortex type 5 – 6 had been identified for a period of 15-30s which requires immediate preventive measures to ensure sustainability of the Temenggor Dam. The study found that flow pattern at the upstream of the Temenggor Dam was influenced by the position of water inlet from dam's upstream, flowrate of the dam and the depth from the water level.

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LIST OF ABBREVIATIONS

EPA	Environmental Protection Agency
ICOLD	International Commission on Large Dams
IHA	International Hydropower Association
MSMA	Manual Saliran Mesra Alam

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Dams are a type of megastructure which impose various functions such as flood control, hydroelectric generator, irrigation, water supply and recreation. Besides, huge amount of potential energy due to its impoundment system may benefit human, but it poses catastrophic danger to the downstream when dam failure occurs (Shahrim and Ros, 2020). For hydroelectric dams, it is important to ensure they are highly efficient to generate sufficient electricity as stated in the design requirements.

To ensure high efficiency and safe hydroelectric dams, factors such as flow pattern of the dam and its impacts towards sedimentation, erosion and vortex formation should be acknowledged. In order to assess these factors, physical hydraulic model should be made. Physical model can be referred as a scaled representation of hydraulic flow scenario in which the flow field and geometry conditions must be scaled accordingly (Chanson, 1999).

For this study, the flow pattern of Temenggor Dam was chosen to be assessed via physical model approach. Temenggor Dam is one of the cascading hydroelectric dams along Perak River (Shahrim and Ros, 2020). It is located at the upper most upstream of Perak River followed by Bersia Dam (20 km downstream) and Kenering Dam (45 km downstream from Bersia Dam). Temenggor Dam (5˚24’ N, 101˚18’ E) is a rock-filled embankment with a catchment area of 3506 km^2 (Nadzri, 2002). In order to assess the flow pattern, hydraulic physical model of Temenggor Dam with a scale of 1:100 (model to prototype ratio) has been made and its flow pattern along the model has been analysed.

1.2 Problem Statement

Temenggor Dam has four penstocks with each penstock is connected to vertical francis type turbines which able to generate electricity of 348 MW (Nadzri, 2002). Therefore, high efficiency turbines are crucial in order to ensure sufficient electricity can be generated. However, due to the factors of geometry condition and position of inlet (upstream flow) of the Temenggor Dam has resulted sedimentation and erosion at the dam. The formation of vortex near to the penstocks to reduce the efficiency of the turbines. Unstable flow pattern at the upstream of the dam and undesirable distribution of inflow velocity along the dam has led to a significant impact towards erosion and sedimentation. It also influences the formation of vortex in terms of its position and type.

To address these issues, the flow pattern along the dam should be uniformly distributed in order to have minimum impact towards the dam and its surrounding. Proper mitigation measures towards erosion and sedimentation at the dam should be applied while reducing the formation of vortex in order to maintain the sustainability and efficiency of the Temenggor Dam. However, to solve these issues, the flow pattern of the hydraulic physical model of Temenggor Dam needs to be studied and analysed based on the design discharged and different position of flow from the upstream of the dam.

1.3 Objectives

The purposes of this study are:

1. To identify the flow pattern of hydraulic physical model of Temenggor Dam.
2. To evaluate the impact of flow pattern towards hydraulic physical model of Temenggor Dam.

1.4 Scope of Work

The study involves data collection from the hydraulic physical model of the Temenggor Dam. The hydraulic physical model of Temenggor Dam has been scaled to 1: 100 (model to prototype ratio), extending from the upstream and downstream portion of Temenggor Dam. However, the hydraulic physical model construction has been previously developed by the assistant engineers from the School of Civil Engineering Universiti Sains Malaysia. Therefore, the detailed construction method of the model will not be discussed in this dissertation. There are two stages (water elevation) that would be tested for this study which are at 0.38m and 0.34m.

There were 24 measurement points have been chosen for data collection. The velocity of flow at every measurement point with different depth from the water surface (20%, 60% and 80%) were measured by using Nixon Streamflow Velocity Meter. The data which has been collected will then be represented in the form of contouring by implementing Surfer 13 software. Based on these representations, flow pattern along the dam can be understood better. From the flow pattern, it will assist in verifying areas which prone to sedimentation and erosion. Besides, the vortex formation along the physical model of Temenggor Dam has been acknowledged in terms of its position, duration and type.

1.5 Expected Outcome

The outcomes of this study are to produce contouring based on the flow pattern along the Temenggor Dam with different water level (stage) and position of inlet. From the contour of the flow pattern, areas that will be highly prone to sedimentation and erosion can be identified. This study also assists in determining the location of vortex despite of different stage (elevation) and position of inlet (upstream) flow into the dam. By understanding the flow pattern, mitigation measures in reducing erosion and sedimentation along the dam can be proposed. Besides, a stable and well-distributed flow pattern along the dam can also be made in the purpose of having minimum impact towards the Temenggor Dam and its surrounding.

1.6 Significance of Study

From this study, the importance of flow pattern especially, at the dam has been acknowledged as flow pattern along the dam will determine the areas which prone to sedimentation and erosion. The influence of geometry in terms of the position of the inlet at the upstream of the dam towards the flow pattern can also be recognised. By having sufficient knowledge related to the flow pattern, mitigation measures to reduce the impact of sedimentation and erosion along the Temenggor Dam can be proposed. Besides, the hydraulic physical model also helps to identify the formation and location of vortex in which the precaution measures can be taken to reduce the effect of vortex at the dam. Hence, these approaches may assist in ensuring the sustainability and reliability of dam with high efficiency and low maintenance cost.

1.7 Dissertation Outline

The dissertation consists of five chapters for better understanding about the flow pattern study based on the hydraulic physical model. The chapters are:

Chapter 1: This chapter explains briefly related to the background of the research includes the objectives of the research. It also highlights the scientific problems related to the study, the scope of work involved, the outcomes expected from the study together with importance of the related research.

Chapter 2: This chapter outlines the literature review from various researchers related to the flow pattern, erosion, sedimentation and the formation of vortex. This chapter acts as the theoretical context for the dissertation, highlighting the basic research problem and the information related to the erosion, sedimentation and vortex formation.

Chapter 3: This chapter depicts the methodology of the study including the information related to the physical model of Temenggor Dam, the equipment used and the calibration involved. Besides, the experimental setup and method of data collection has been explained in this chapter.

Chapter 4: This chapter signifies the data obtained, data interpretation and the findings from the laboratory test. Based on the problems identified, the objectives of the study have been discussed in detail in this chapter from result analysis and contours generated via Surfer 13 software. The mitigation measures towards sedimentation, erosion and vortex formation also discussed in this chapter.

Chapter 5: This chapter provides the conclusion of the research study including the recommendation required in order to have better understanding of the related field of study.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Overview

In this chapter, topics related to the study will be reviewed and discussed. The topics include type of dams with their functions, physical hydraulic model, flow pattern, vortex formation, sedimentation and erosion together with their causes and effects towards the safety and efficiency of dam.

2.2 Dam

A dam is a massive impounding construction or barrier which is built on a watercourse to contain vast amount of water and regulate the water flow. Typically, a reservoir and a dam are existed together (Bharti et al., 2020). Besides, dam can be made either by human or natural phenomena (landslides or glacial deposition). Throughout the generations, dams have proven their functions as water storage for water supply, irrigation, hydroelectric and flood protection. For the hydroelectric generation, water level has been raised to create sufficient head which may rotate the turbines in an electricity generating power plant that usually located at the dam's toe (Deangeli et al., 2009). The capability of every dam should be well-understood and this can be achieved by acknowledging the classification of dam.

2.2.1 Classification of Dam

Many factors can be implemented in order to classify dams such as their size, height, functions served, hydraulic design, material of construction, rigidity and structural design (Bharti et al., 2020).

a) Size

Dams can be classified to large dam and small dam. Based on the International Commission on Large Dams (ICOLD), dam is considered as a large dam if its height is greater than 15m. If the height between 10m to 15m, it should be met certain criteria before being considered as a large dam. The criteria are crest length should be bigger than 500m, reservoir capacity is larger than one million meter cubic and flood discharge greater than 2000m^3/s (Bharti et al., 2020).

b) Height

Based on Bharti et al. (2020), for classification of dams based on height, they can be classified as high dam (height greater than 100m), medium dam (height between 50m and 100m) and short dam (height less than 50m).

c) Hydraulic design

Dams can be classified into overflows and non-overflow dams (Bharti et al., 2020). Overflow dams (Figure 2.1) is referring to the dams which allow excess water in the dam to flow over the crest of the dam which may serve as a spillway. Non-overflow dams (Figure 2.2) is referring to the dams which do not allow flow over the crest of the dam and separated spillway will be provided to channel the excess water from the dam(Khassaf, 2020).

Figure 2.1: Overflow dam – Kouris Dam (The Villa Group, 2020)

Figure 2.2: Non-overflow dam – Hoover Dam (Britannica, 2019)

d) Material of construction

Dam construction material is one of the factors that can be used for the classification of dam. The construction of materials can be masonry, concrete, earth, rockfill, timber, steel and composites (Bharti et al., 2020). The choice of materials for the dam depends on the foundation, the kind of functions that will be served by the dams, material is readily available and cost of the construction (Jamal, 2018). For rockfill dam (Figure 2.3), it requires stronger foundations compared to the earth dam and usually it is composed of firmly packed gravel and impervious materials such as concrete and clay which help to block water and provide strength to the dam. The advantages of rock-fill dams are they are cheap if the materials are attainable, they can be built in bad weathers and usually require shorter construction period (Rodriguez, 2019).

Figure 2.3: Rockfill dam – Temenggor Dam
(Perbadanan Bekalan Air Pulau Pinang, 2019)

e) Rigidity

For classification of dam under rigidity, it can be classified either rigid or non-rigid dams. The rigidity of a dam depends on the material of construction. For rigid dams, they are made from rigid materials such as stone, concrete and masonry. For non-rigid dams, they are made from earth, rock-fill and tailings (Khassaf, 2020).

f) Function

Dam can be classified based on the functions it serves. Dams can be classified to storage dams, detention dams, diversion dams, debris dams and coffer dams (Bharti, et al., 2020). For storage dams, they are crucial for water storage especially, during rainy season. The impounded water can be used for irrigation, water supply and hydropower. Detention dams function as flood control which help to attenuate the peak flow in the upstream rivers by storing some of the flood water. Hence, flood at the downstream of the dam will be protected. Diversion dams are used to divert water of the river into another watercourse for conservation use. Debris dams function to contain debris (gravel, driftwood) which flows in the river and the downstream of the dam will have clear water. Coffer dams are a temporary dam that are constructed at the construction site in order to ensure the construction is dry by eliminating water (Deangeli et al., 2009).

g) Structural design

Dams can also be classified based on the structural design such as gravity dams, earth dams, rock-fill dams, buttress dams, arch dams, steel dams and timber dams (Bharti et al., 2020). Different design of dam can be observed from Figure 2.4.

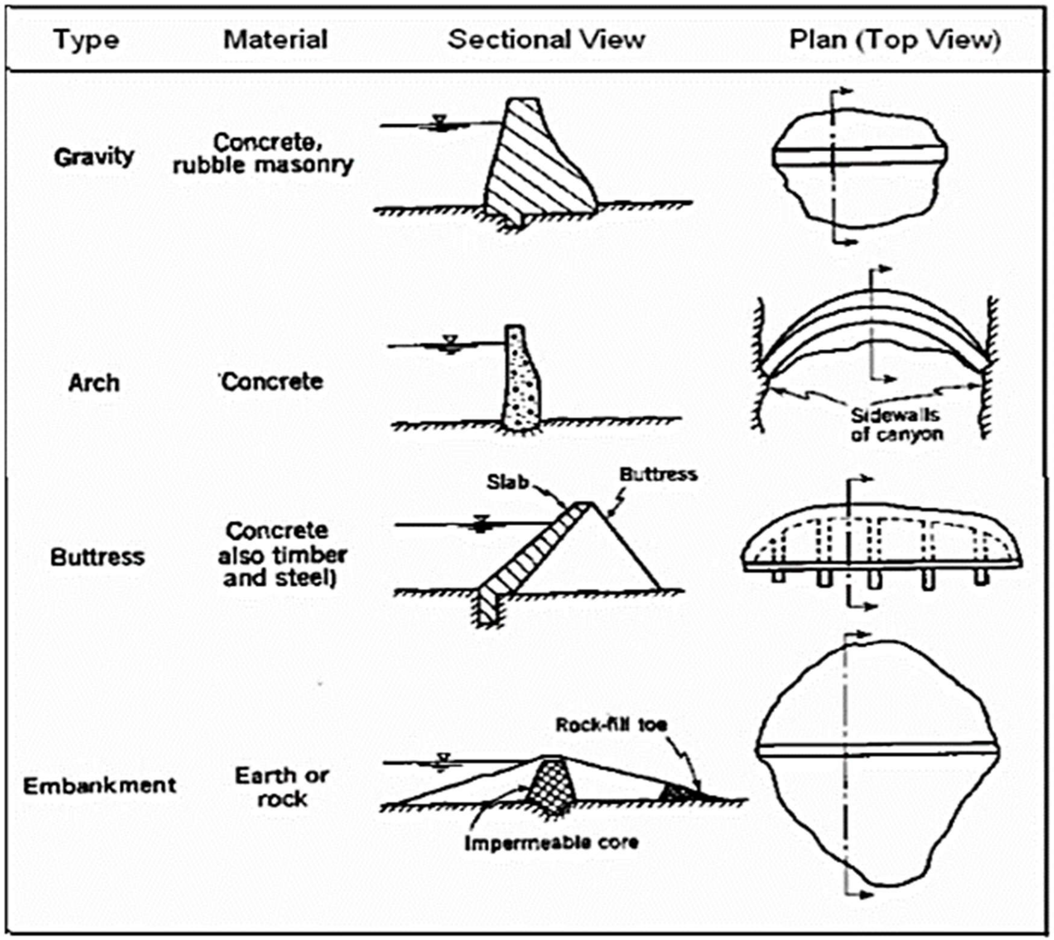

Figure 2.4: Type of dam based on structural design (Khassaf, 2020)

2.3 Physical Hydraulic Model

According to Chanson (1999), a physical model can be referred to a scaled presentation of a hydraulic flow condition whereby the criteria such as boundary conditions, flow condition at the upstream and the flow field should be scaled accordingly. The flow conditions are said to be equivalent in both physical model and prototype if geometric similarity, kinematic similarity and dynamic similarity are achieved by the model. Generally, size of physical hydraulic model is smaller compared to the prototype and there also scenario where physical model is studied in a laboratory under controlled environment (Kamel, 2013). The ability of visualizing complex behaviour condition has made the physical model as the first choice for analysis purpose since complex flow problems cannot be simulated by numerical modelling (Gessler and Johansson, 2019). The use of physical hydraulic model can be applied for dam, stilling basin, spillways and vortex shaft drops. Besides, the physical hydraulic model can also depict the influence of geometric features towards flow pattern properties and flow resistance (Peña and Anta, 2021).

Although hydraulic physical model has many potentials, it may also possess disadvantages. Hydraulic physical model requires larger number of experiments, longer period of time and more expensive compared to numerical modelling (Carmo, 2020). In a hydraulic physical model, full dynamic similitude between prototype and model is physically impossible as the gravity effects are significant which cause scale effects – difference of the force ratios between prototype and model (Torres et al., 2018). Hence, sufficient knowledge and accurate scaling are essential to ensure the efficiency of the hydraulic physical model.

2.4 Flow Pattern

According to the Environmental Protection Agency, EPA (2017), flow is referring to the function of water volumes and velocity which may impact the dam bed and levees. Besides, Thomson (2006) had stated that flow pattern can also be defined as the streamlined flow in which fluid slides in layers which can be either in turbulent or laminar. In many cases, most of the flow patterns unable to be modelled numerically, hence the implementation of physical model is essential due to the complexity behaviour of fluid in a system (Kamel, 2013).

Besides, flow pattern can be significantly influenced by the flow rate of the system, pressure, surface tension, density, geometry and distance from the inlet (Tan and Dong, 2021). The upstream flow diversion and rainfall can also affect the flow pattern formed (Patil et al., 2022). Flow pattern contouring (Figure 2.5) is essential to have better representation of the flow pattern based on the data of the flow velocity from the laboratory test. Flow pattern and its contour which had been developed by using numerical model software such as CCHE2D had assisted in better understanding on the studied hydraulic structures such as upstream of dam, outlets and stilling basin at Masudagawa dam (Kantoush and Sumi, 2010).

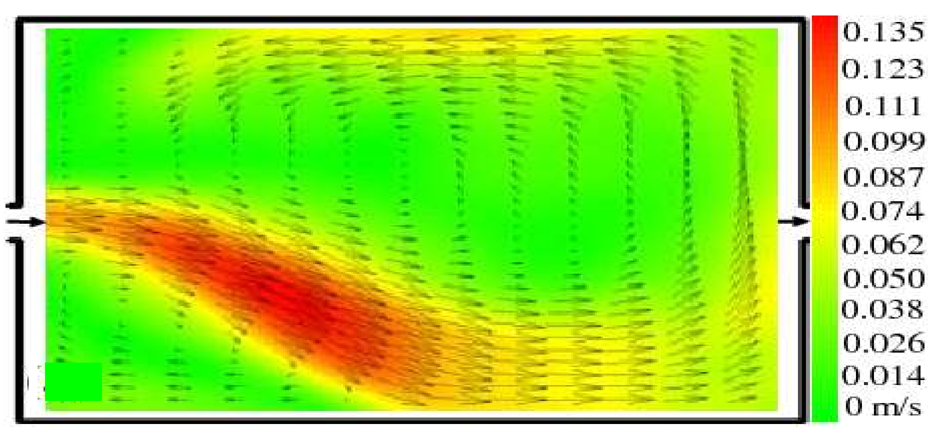

Figure 2.5: Flow pattern contour (Kontoush, 2011)

2.4.1 Importance of flow pattern

Flow pattern can assist in designing better and more sustainable hydraulic structures such as dam, spillway and stilling basin. Many studies have been made in order to depict the use of flow pattern in the design of hydraulic structures. According to Kantoush and Sumi (2010), flow pattern formed will assist in determining the sediment deposition based on the flow velocity. Besides, the influence of geometry towards the flow stability and flushing process can be studied based on the flow pattern formed. Thus, optimal design of hydraulic structures can be proposed.

Besides, flow pattern can also help in determining the areas with high and low velocities. For dam purposes, areas with flow pattern of low velocity are highly potential to undergo sedimentation and otherwise. The turbulency of the flow can also be observed for analysis purpose (Aghamajidi, 2019). From the flow contour, circulation zones along the hydraulic structures, especially at the dam's outlet can be observed, resulting the formation of vortex (Azarpira et al., 2014). Thus, it shows how importance flow pattern in analysis for hydraulic models.

2.5 Sedimentation

Reservoir sedimentation can be referred as a process of transportation, deposition and compaction of sediment which has been contained by dams. Deposition of sediment occurs at dam due to the low flow velocity due to the increased of flow depth in which reduces the transport of sediment capacity and accelerates the sedimentation process(Schellenberg et al., 2017). According to Sumi and Hirose (2009), sedimentation at reservoir can be known as a complex process which is influenced by the production of watershed sediment, transportation rate and deposition mode. Besides, it also depends on the dam geometry and operation, flood frequencies and changes of land use throughout the lifespan of the dam. Construction of dam has disrupted the continuity of the existing river system which caused the sediment from the dam upstream to be deposited in the quiet water of the dam (Kondolf et al., 2014). The hydraulic modeling study conducted by Iqbal (2019) had examined the sedimentation effects due to the sediment transport towards the two cascade reservoirs which were located at Poonch River via physical modeling and it has shown the importance of designing proper dam's geometry in order to reduce the sedimentation effect. However, this study had been limited to the deposition of sediment without relating them with the flow pattern and velocity of flow (Iqbal, 2019).

2.5.1 Causes of sedimentation

Sedimentation can be caused due to the natural and anthropogenic factors. Natural factors can be such as geomorphology, hydrology, hydrogeology, geology and soil characteristics. For anthropogenic factors, they can be such as tillage practices, overgrazing and logging (Obialor et al., 2019).

a) Natural Factor

Geomorphology is referring to the topography of the land surface including its location, size and shape. Hydrology factors such as the effect from annual rainfall, ratio of watershed area to reservoir area and the volume of stream discharged into the reservoir may significantly impact the sedimentation in reservoirs. In terms of hydrogeology, it will influence the sedimentation from the effect of groundwater contaminants towards the sedimentation process. Geology factor will cause sedimentation in terms of the construction of hydraulic structures and their impacts towards the surrounding. For soil characteristics, the type of soil at the reservoir and its potential to be eroded by the water flow may also lead to sedimentation (Obialor et al., 2019).

b) **Anthropogenic Factor**

Tillage practices is an activity which carried out between the harvest and following sowing period. Improper practices of tillage may result the wash of loose soil into the nearest water bodies. Besides, overgrazing by animals, may also result the exposed soil to undergo erosion and flow into the upstream rivers before deposited in dams. Human activities such as logging is one of the main factors which contribute to high rate of sedimentation in dams (Obialor et al., 2019). Besides, in Thailand, 1% of deforestation has resulted an increment up to 8.7% in annual sediment load in Wang River sub-basin and meanwhile in Malaysia, deforestation near to Sambas River has resulted increment about 10.3% in sediment concentration for every 1% deforestation (Zhao et al., 2022). Hence, indicating the significancy of logging towards sedimentation.

2.5.2 Impact of sedimentation

Generally, sedimentation has adversely impacted the efficiency and safety of the dam and its surrounding. Many studies indicated that sedimentation has reduced the dam storage capacity as indicated by Obialor et al. (2019), Zahabi et al. (2018) and Petkovsek and Roca (2014). Water from the reservoir upstream catchment will carry the eroded and deposited material into the dam. Eventually, due to the pressure, layers of deposited sediments will be formed in the dam in which if the process of deposition prolonged, it may lead the whole dam to be congested with sediments and becomes inefficient (Garg, 2013). It is estimated that all reservoirs in the world lost about 1% of their total storage capacity every year because of sedimentation (Petkovsek and Roca, 2014). Reduction of reservoir storage capacity may lead to high cost maintenance due to more frequent and high cost of dredging and removal (Akademi Sains Malaysia, 2017).

Besides, sedimentation can also affect the efficiency in generating hydropower. Due to loss of dam storage due to the effect of sedimentation, the head available at the dam will reduce and adversely impact the hydropower generation (Obialor et al., 2019). According to Rashid et al. (2021), the depleted dam storage does not only reduce the hydropower generation, but also can lead to the impairment of dam's mechanical components. Without sufficient energy produced by the dam, the sustainability of the dam can be questionable. In addition, sediment which flows through the turbines may cause the mechanical equipment to undergo abrasion which lead to the reduction in the efficiency of the power generation, longer period of shutdown time and high cost maintenance (Petkovsek and Roca, 2014; Dorji and Ghomashchi, 2014)

Sedimentation can also cause instability of dam as sediment loads, resulting in higher uplift pressure towards the dam especially, during high turbid inflow towards the dam or a seismic event. Sedimentation at dam may also disrupt the plants and animals species which are sensitive to flow pattern and sediment accumulation (Obialor et al., 2019). High quantity of sediment will prevent the light from reaching aquatic plants and may cause the fish gills to be clogged (Fondriest Environmental, 2014).

2.5.3 Requirement for sedimentation

Settling of sediment occurs when the velocity of flow reduces in which denser particles cannot be supported by the bed turbulence (Fondriest Environmental, 2014). The settling velocity of sediments depends on their size and density of the particles. Larger particle size and denser particle will settle faster compared to less dense particles (Gulliver et al., 2010). Based on the study which has been conducted by Jodeau et al. (2016) , the sediment settle when velocity of flow reached between 0.18 and 13.1 mm/s depends on the type of sediment particles. Besides, based on research conducted by

Hjulström (1940), transportation or deposited of sediments are influenced by the grain size and flow velocity as shown in Figure 2.6. For example, 1mm grain of sand will be deposited the velocity of flow below than 10 cm/s while for a 10mm gravel grain, it will be deposited if the velocity of flow less than 80 cm/s (Earle and Panchuk, 2015). According to Manual Saliran Mesra Alam (MSMA) Second Edition (2012), sedimentation will occur if the velocity of flow less than 0.6 m/s.

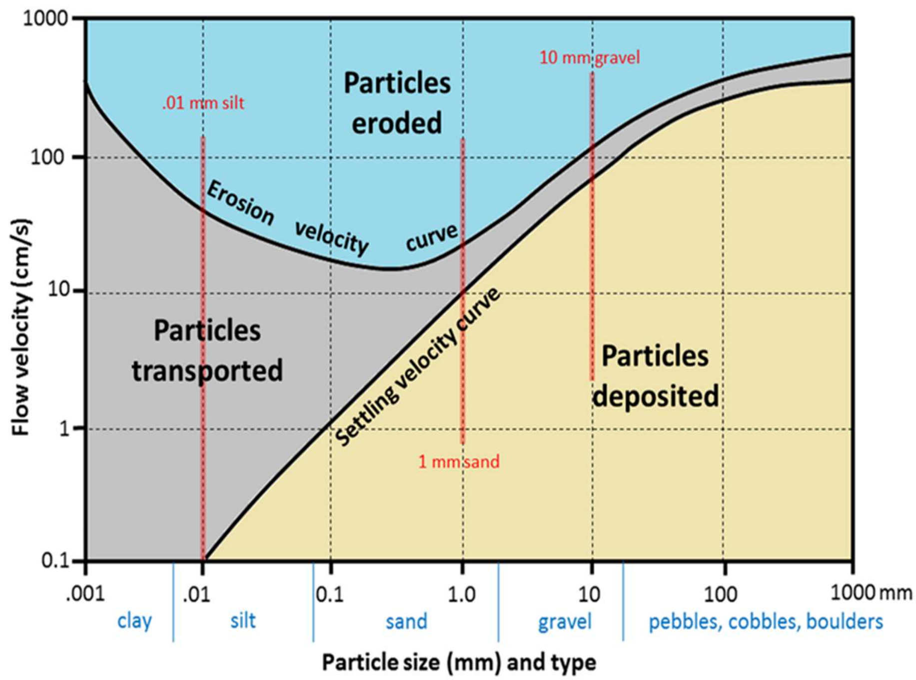

Figure 2.6: Relationship between particle size and the tendency to be eroded, transported or deposited with different velocity of flow (Earle and Panchuk, 2015)

2.6 Erosion

Erosion can be defined as a geological process in which surface material (earthen material) will be removed and transported from the origin to another place by natural agencies such as water or wind (Britannica, 2022). According to International Hydropower Association (IHA) (2019), erosion consists of removal and transportation of solid material due to the action of water, wind or ice which also includes the abrasion of the sediments they transport. For area within dams, water erosion usually happens. Water erosion is referring to the soil material erodes due to water and it is significantly influenced by the soil properties, local landscape, weather conditions and velocity of flow (USDA, 2001). Eroded materials or also known as sediments in dams usually result from the in-stream erosion processes or from within the catchment which connected to the upstream rivers that flow into the dam (Zarfl and Lucía, 2018). Hence, deposition of sediment in dams can be reduced by reducing erosion rate at the upstream which can be achieved by implementing proper land use based on the conservation basis(Julia and Novita, 2018).

2.6.1 Causes of erosion

Erosion rate at dam usually is influenced by the form of upstream morphology, flow volumes and velocity and sediment type which affect the erosion pattern and movement. Due to the dynamic processes, river morphology especially, nearing to the dam become unstable which effects the erosion significantly. For dam, erosion at the rim of the dam should be concerned. Rim erosion can be caused due to the drawdown of dam levels accompanied with saturation effect. Besides, repeated fluctuation in dam levels may also cause erosion at the shoreline of the dam occurs (IHA, 2019). Generally, erosion at dam is because of high water flow from upstream especially, during rainy season. The flow of water may result in in-stream erosion which may erode the levees and upstream of the dam (Zarfl and Lucía, 2018). Besides, according to Julia and Novita (2018), the main factors of soil erosion at dam are due to climate change, soil type, topography, vegetation and human activities especially at the upstream of the reservoirs. Deforestation at the upstream of the dam has increased soil erosion during rainfall. As vegetation cover at the bank has been removed, material at the lower bank will be eroded easily due to the action of flowing water (Xiong, 2011). According to Akademi Sains

Malaysia (2017), high flows will destabilise the levees, resulting scouring at these areas. Generally, scoured banks without vegetative cover will be prone to high flows and carried away together with the flows especially, during rainfall event. Hence, this event will significantly impact the sustainability of the dam especially a hydroelectric dam.

2.6.2 Impact of erosion

Initially, erosion may result in direct removal of bank and bed material due to the action of flowing water. Bank scour can be detected from the undercutting at the bank toe. However, the unthreatened bank scour may result in bank collapse – a large amount of earth material which become unstable and topple into streams or water bodies due to the effect of saturation(Julian et al.,2006 ; Xiong, 2011). Besides, construction of dam has caused most of the shoreline became highly prone to landslide and infiltration of water from the impounding water at the dam which has worsen the condition. As these slopes are exposed to the erosion due to water flow at the dam, slope failure may occur. Slope failure at dam is catastrophic as it may generate impulse waves, causing the water to overtop the dam, leading to the dam failure and endangering public safety (IHA, 2019). In China, due to the frequent changes of water level and flow velocity had caused landslide which destroyed one of the hydroelectric dams in Three Gorges Dam region. Due to the climate change and uncontrolled erosion at the bank, more landslides and bank slumping events has occurred which threatened the sustainability of hydropower dams in the region (Qin, 2014).

Besides, erosion may also lead to the deposition of sediment in dams. In Indonesia, due to high rate of erosion has led to the accumulation of sediment in Sempor Reservoir, resulting reduction of the reservoir's storage capacity (Julia and Novita, 2018). In United Sates of America, studies depict that scoured banks and eroded materials at the upstream has contributed to the 75% sediment load in the rivers. When a dam is constructed, these eroded materials will be deposited at the dam due to low velocity of flow, resulting sedimentation (Akademi Sains Malaysia, 2017). The same issue has been discussed by Basri et al. (2019) where soil erosion has led to the serious accumulation of sedimentation in Temenggor Reservoir Basin.

2.6.3 Requirement for erosion

As mentioned in previous section 2.6.1, erosion depends on the velocity of flow accompanied with rapid changes in flow pattern. In this section, velocity of flow which may erode the soil particles will be discussed. The relationship between velocity of flow and the tendency for the soil particle to be eroded can be observed from Figure 2.6. For example, 1mm of sand will start to erode when the velocity of flow exceeds 30 cm/s. According to Earle and Panchuk (2015), as particle size increases (0.001 mm to 0.5mm), the minimum velocity of flow required to erode the particle reduces. For a particle larger than 0.5mm, the velocity of flow to erode the particle increases with larger particle size. According to MSMA 2nd Ed., in order to avoid scour at various ground cover, the ideal velocity should be less than 2 m/s.

2.7 Vortex

Vortex is a rotational motion of fluid around an axis and can also be referred as the vorticity in the fluid (Nitsche, 2006). Formation of vortices usually occur at the intakes of the hydroelectric dams (Azman et al., 2020). Besides, vortices are usually formed at low water levels as water level below critical submerged depth will generate free surface vortices (Domfeh et al., 2020). According to Sarkardeh (2017), critical submerged depth is referring to the depth which prevent the formation of vortex or also known as the minimum operation depth. However, the vortex behaviour is influenced by its strength. Hence, the classification of vortex needs to be acquired for this study.

2.7.1 Vortex classification

Methods in classifying vortices are done via visual techniques and measurement of certain quantity which related to the strength of the vortices. Visual classification method is preferable than measurement method since it is simpler and does not require complex measuring devices in order to identify the vortex strength. Hence, for the purpose, Alden Research Laboratory has developed specification in classifying vortices based on six different stages with increasing intensity as shown in Table 2.1 and the schematic diagram for the stages can be observed from Figure 2.7 (Kiviniemi and Makusa, 2009). The classification was made on the basis of the strength and transformation of the vortices where vortex at the higher stage produce higher impact towards the hydraulic machinery (Gulick et al., 2014).

Table 2.1: Alden Research Laboratory – Classification of free surface vortex (Kiviniemi and Makusa, 2009)

Stage	Name	Description
1	Surface swirl	A constant swirl on free surface
2	Dimple	A small depression in the centre of the swirl
3	Dye core	Dye core reaches into intake
4	Trash pulling core	Vortex pulls floating trash into intake
5	Bubble entraining core	Vortex pulls air bubbles into intake
6	Full air core	Vortex pulls constant stream of air into intake

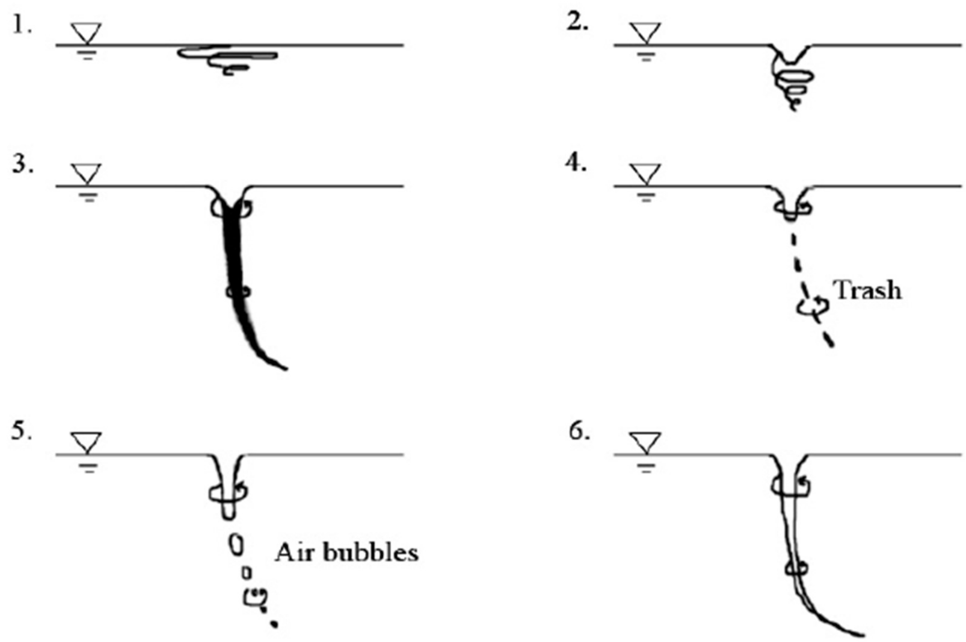

Figure 2.7: Stages of free surface vortex based on Alden Research Laboratory (Kiviniemi and Makusa, 2009)

However, there is also latest study conducted by (Sarkardeh et al., 2010), where vortices are classified into three classes – Class A , Class B and Class C. These classes (Figure 2.8) are classified based on their impact towards the dam intake (Gulick et al., 2014). Class C can be considered as safe with slight dimple at water surface. Surface vortices of Class B are stronger and the vortex extends downwards towards the intake which may drag trash into the intake. Class A vortices are referring to the highest strength vortices with negative impact towards the intake. This is because air bubbles will be entrapped and entering the intake in a steady state. Class A vortices should be avoided (Sarkardeh et al., 2010; Azman et al., 2020; Domfeh et al., 2020).

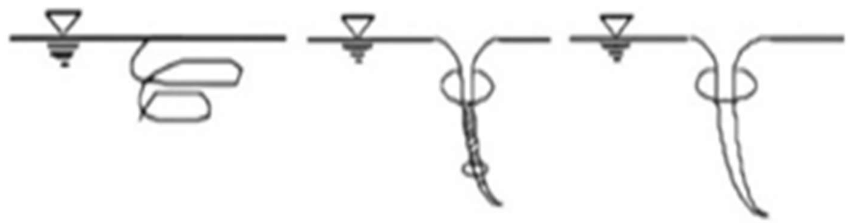

Figure 2.8: Vortex classification (Azarpira et al., 2014)

2.7.2 Causes of vortex

Vortex is formed when the spinning motion of fluid higher than resisting force. This phenomenon will occur due to the asymmetrical flow where water flows through bends, obstructions and intake structures with supercritical flow undergoes swirling. The intake properties especially, its geometry usually will influence the velocity of flow which affects the vorticity around the intake (Kiviniemi and Makusa, 2009).

Besides, vortex occurs at lower water level which depicts the influence of the intake submerged depth. Submerged depth can be defined as the distance between the intake axis and water surface (Sarkardeh et al., 2010). When the water level below critical submergence, the possibility of vortex formation is high (Domfeh et al., 2020). Vortex strength is greatly influenced by critical submerged depth where high vortex strength may result in higher critical submerged depth (Sarkardeh et al., 2010). By having right amount of submergence, there will be enough pressure head for the compression process to support shearing process in which the formation of vortex can be prevented (Kiviniemi and Makusa, 2009).

Furthermore, unstable velocity distribution may also form vortex. The approach velocity flow will greatly influence the strength of vortex formed. Asymmetrical pattern