A STUDY OF FLOW INDUCED VIBRATION AT HYDRAULIC PHYSICAL MODELLING OF KENYIR DAM SPILLWAY

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SCHOOL OF CIVIL ENGINEERING

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by

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ABSTRAK

Empangan, takungan, dan struktur lain seperti limpahan dan pengambilan ialah komponen penting infrastruktur untuk bekalan air, penjanaan tenaga, penyimpanan dan kawalan banjir, serta untuk mencegah kesan negatif masyarakat dan persekitaran yang mungkin disebabkan oleh kegagalan, kerosakan, atau reka bentuk yang kurang memuaskan.

Reka bentuk, pembangunan, operasi, pengurusan, keselamatan, dan kesinambungan empangan adalah semua perkara penting hidraulik yang ditangani oleh kejuruteraan hidraulik empangan. Ini merangkumi semua aspek reka bentuk hidraulik struktur, termasuk getaran, pusaran, interaksi aliran udara, dan penyebaran gelombang yang disebabkan oleh kerosakan empangan.

Tujuan kajian ini adalah untuk mengkaji getaran yang disebabkan oleh aliran pada model fizikal hidraulik Empangan Kenyir. Prosedur analisis dilakukan menggunakan perisian SCADAS yang khususnya di gunakan dalam menilai kesan getaran pada struktur.

Kapasiti pelepasan yang tidak terkawal, sifat geometri yang tidak sah, hujan yang tidak dapat diramalkan menyebabkan banjir melampau di hilir dan juga kegagalan hilir kerana hakisan, masalah pemendapan, pusaran dan kehadiran aliran pergolakan selain kehadiran geseran adalah beberapa faktor penting yang menyebabkan pengurangan kapasiti limpahan.

Keputusan menunjukkan bahawa kedua -dua kes model masih mampu menahan magnitud getaran pada frekuensi yang berbeza kerana nilai puncak magnitud untuk kes q = 60 l/s dan q = 90 l/s masing -masing adalah 2.787 m/s2 dan 3.626 m/s2 masing -masing yang berada dalam julat yang selamat.

ABSTRACT

Dams, reservoirs, and other structures like spillways and intake are crucial components of infrastructure for water supply, power generation, storage and flood control, as well as for preventing negative societal and environmental effects that may result from failure, malfunction, or poor design. The design, building, operation, management, safety, and sustainability of dams are all hydraulic issues that are addressed by the hydraulic engineering of dams. This covers all aspects of a structure's hydraulic design, including vibration, vortices, airflow interactions, and dam breaches or wave propagation caused by a dam break.

The aim of this study is to study of flow induced vibration at hydraulic physical modelling of Kenyir Dam Spillway. The analysis procedures were carried out using the SCADAS software which is specialized in evaluating vibration effect on structure.

Uncontrolled discharge capacity, invalid geometrical properties, unpredictable rainfall leading to extreme floods downstream and also downstream failure because of erosion, sedimentation issues, vortex and the presence of turbulent flow besides the presence of friction were some of the significant factors that led to the reduction in spillway capacity.

The results show that both cases model is still capable of withstanding the vibration's magnitude at different frequency since the peak value of magnitude for case Q = 60 L/s and Q = 90 L/s are 2.787 m/s^2 and 3.626 m/s^2 respectively.

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CHAPTER 1

INTRODUCTION

1.1 Background

Over the last decade, hydraulic structures, specifically dams, have become one of the most essential water storage areas to meet the growing need for clean water, water stress issues, flood control systems, and hydroelectric power generation. Spillways are the most significant components of large structures such as dams, as their primary job is to discharge surplus or flood water (that cannot be kept in the storage volume) in a regulated or uncontrolled manner in order to ensure the overall system's safety (Mirabi et al., 2021). Prior to the safety issues, the performance of the spillway should be addressed as one of the primary aspects prior to its construction and during its service life.

Spillways, on the other hand, should be built at a low cost and be able to function smoothly for the duration of their design life. By conducting a critical assessment on fluid-structure interaction analysis, the hydraulic parameters (discharge, flow depth, and velocity) and flow characteristics (subcritical, critical, and supercritical conditions) as well as their vibration impacts on the structure's members should be accurately known (Mirabi et al., 2021).

In addition, uncontrolled discharge capacity and invalid geometrical properties contributed to the fluid overtopping issue due to frequent flood events, rainfall uncertainty causing extreme floods at the downstream location, downstream failure due to erosion and sedimentation problems, vortex and the presence of turbulence flow, and the presence of friction were some of the important issues (general and technical) that contributed to the decrement of the spillway capacity. Upgrades or modifications to the current spillway may be a better solution. However, because most dams are old and the flow is changing owing to climate change, the modification work necessitates a thorough understanding of hydraulics and flow characteristics.

1.2 Problem Statements

The Kenyir dam has an ogee-type spillway to control the reservoir supply level. Water spillage events have occurred over the years at the dam where the water level has exceeded the operating level of the dam. However, the incoming stream of water with high velocity and energy from the uncontrolled no-gate spillway towards the downstream channel have been affecting and causing insecurities in the dam structure. Due to the effect of flow-induced vibration, dam structures must be inspected on a frequent basis to ensure their reliability.

If the natural frequencies of the structure coincide with the operational frequencies of the structure, vibration caused by the fluid (water) on the dam structure might lead to catastrophic failure. The consequences of water spilling and surging on the Malaysian Kenyir Dam in terms of vibration are investigated in this study. Only the spillway and intake parts of the Kenyir Dam are considered for this purpose.

1.3 Objectives

The objectives of this study are:

1. To investigate flow induced vibration at Hydraulic Physical Model of Kenyir Dam Spillway.

2. To study the flow characteristics of Hydraulic Physical Model of Kenyir Dam Spillway.

1.4 Scope of Work

The scope of work for the hydraulic model is to study the data collected from the physical model of Kenyir Dam. According to the actual dimensions, the design scale for this model is 1:30. The data set involves two different types of measurement which are the velocity and vibration at the selected point along with the model. Two different discharge rates that should be tested which are 60 L/s and 90 L/s for both vibration and velocity analysis.

Moreover, this study will give us description and picture of the Kenyir Dam flow characteristic. Beside that, the consequences of water spilling and surging on the Malaysian Kenyir Dam in terms of vibration are investigated in this study. The main test to determine and achieve the related objective is through physical modelling of the Kenyir Dam Spillway.

1.5 Dissertation Outline

The thesis is distributed specifically into five chapters to enhanced research inspection and comprehension. The outline of each chapter is discussed below:

Chapter 1: Introduction – This chapter provides an overview of the thesis, then it continues with the problem statement and understand why this study is conducted, the research objectives to set the desired work goal, the scope of the work, justification of this research and finally limitation of work.

Chapter 2: Literature review – Provides a critical fundamental interpretation of the information needed based on the previous thesis and studies that are performed by other researchers according to the related topic which is physical modelling on the Kenyir dam spillway.

Chapter 3: Methodology – Describes the research methodology of physical modelling. It will be discussed in further detailed on the flow of experimental work that will be done to achieve the objective of this research. This chapter is the most important section because it contains detailed procedures to complete this study using instrumentation.

Chapter 4: Result and Discussion – This section also one of the critical parts of this thesis because it will be highlighted the outcome of the experimental work when the result is obtained. The final result will be discussed along with the supporting facts and findings.

Chapter 5: Conclusion and Recommendation – This is the final chapter of the thesis which conclude all the result and information obtains from the research and recommendation for the future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of chapter

The importance of spillways, spillway varieties, vibration effect on the model, hydraulic jumps, location of hydraulic jumps affected by the jump height (JHC), and Froude number will all be discussed in this chapter. Finally, stilling basins and their components, as well as the many types of stilling basins, will be explored.

2.2 Scaled Physical model of dam

The dam structure is a challenging structure to study since it is a big structure, and experimental analysis on a real-scale dam is complex and time-consuming. As reference to a dam's physical model, it is critical that the actual dam be reconstructed in the form of a physical model in order to analyse and simulate the dam's behaviour under various conditions. Based on the Froude number, all physical models must have the same geometric and kinematic ratios as the actual object in order for both physical and real models to be in the same flow regimes. The Froude number is a combination of gravitational and inertial forces. Furthermore, dimensional analysis shows that the Reynolds Numbers in the model and prototype for viscous forces should be the same.

2.2.1 Froude Number

It is impossible to achieve both the Froude and Reynolds number scaling criterion at the same time because the same fluid is used on both the model and prototype. As a result, the majority of models are run with Froude's similarity in account, implying that gravitational influences are dominating and that water viscosity and surface tension are unimportant (Dalrymple 1985).

As gravitational forces are the most relevant in free surface work, the Froude Number, rather than the Reynolds Number, must be made equal to the prototype. This ensures that surface profiles, rotational flow, and waves are accurately represented.

$$Fr = \frac{V}{\sqrt{gD}} \qquad \text{Eq. 1}$$

Where:

V = Water velocity

D = Hydraulic depth (cross sectional area of flow / top width)

g = Gravity Acceleration

When:

Fr = 1 (critical flow),

Fr > 1 (supercritical flow),

Fr < 1 (subcritical flow)

2.2.2 Reynold Number

For turbulent flow, the Reynolds Number is unimportant as long as both the model and the prototype have values within the same flow domain. Laminar flow may occur in the model but turbulent or transitional flow may occur in the prototype as the Reynolds Number of a model approaches the point of transition from turbulent to laminar flow. This is clearly unsatisfactory, and a minimum Reynolds Number for practical purposes must be chosen.

$$\mathrm{Re} = \frac{\mathrm{VL}}{\mathrm{K}} \qquad \text{Eq. 2}$$

Where:

V = velocity

g = gravitational constant

L = characteristic length

K = kinematics viscosity

Finally, the Froude and Reynold Number theoretical principles are used to model the spillway, chute, and stilling basin. The Froude Number, Fr, is a good representation of the first principle, inertia, and gravitational forces. Second, the viscous force is represented by the Reynolds Number, which is insignificant in free flow until it falls within the laminar flow area.

2.3 Spillway

Spillway is one of the key structural components of a dam that allows water to flow back into the river without causing damage to the dam. Spillways are structures that allow excess streamflow to pass through a dam. Spillways are designed to discharge high floods in key projects on major rivers. The spillway is usually built into the main construction of a concrete gravity dam, allowing an overflow that is either uncontrolled or managed by gates. The spillway at an embankment dam is usually a channel or conduit located in or on an abutment or at a remote place on the reservoir rim. The types of spillways include overflow with an ogee-crest shape and shaft and tunnel with a glory hole, funnel-shaped entrance. The side channel, in which the crest is generally parallel to a discharge channel consisting of a trough leading to a tunnel or chute, has also been employed in rare circumstances (Jansen et al., 2003).

Since the effective storage is up to the usual reservoir level, the top of the dam must be designed to surpass the maximum reservoir level following the design flood used for the spillway design. Furthermore, various elements must be addressed while designing a spillway, including the type of dam and the appropriate spillway type, hydraulic conditions, and external considerations such as topographical and foundation conditions, all of which contribute to the dam's stability. The spillway's design must also meet the Probable Maximum Flood (PMF) criterion in order to resist the projected severe climatic and hydrological conditions.

2.3.1 Type of Spillway

Depending on the site circumstances and other factors, different types of spillways can be constructed. Moreover, based on their location, spillways are classed as overflow or type of channel. Drop, ogee, side channels, shaft, labyrinth, and chute spillways are examples of several types of spillways. These major spillway types are further divided into sub-categories. In Kenyir Dam Spillway Physical Model, we use Ogee type Spillway which is exact as the actual Kenyir Dam Spillway. Ogee spillway represents the shape of the downstream face of the weir. It's a more advanced version of a straight drop spillway. In this case, the weir's downstream face is designed to match the shape of the freely flowing water jet's lower nappe, which is ogee-shaped.

Figure 2.1: Spillway section in Kenyir Dam Physical Model

In theory, the ogee-crested spillway's performance attributes are due to its shape being derived from the lower surface of an aerated nape flowing over a sharp crested weir. The ogee shape results in near-atmospheric pressure over the crest section for a single given upstream head. Because the flow rate is not limited to a single head, the flow rate over an ogee crested spillway varies from that of a sharp-crested weir. At heads lower than the design head, the discharge is less because of crest resistance. At higher heads, the discharge is greater than an aerated sharp-crested weir because the negative crest pressure suctions more flow. Designing a crest that allows small negative pressures at the design flow is a practice called under-designing and it increases the efficiency of the spillway. However, the crest pressures must not be allowed to go too negative. A large negative pressure on the crest can cause cavitation damage, destabilization of the structure, and possible failure. Large negative pressures can also be caused by discontinuities in the crest shape (Kamel et al., 2019).

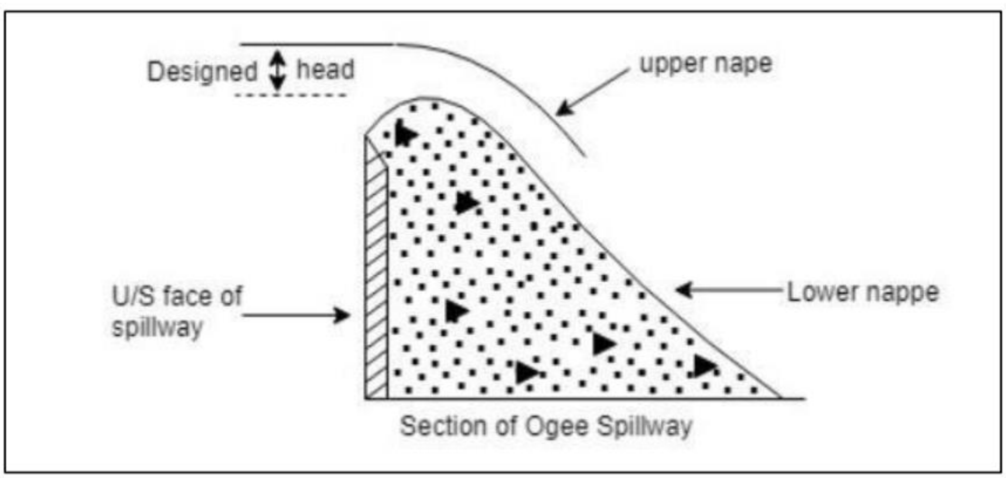

Figure 2.2: Ogee Spillway(Kharagpur 2008)

2.3.2 Straight Drop Spillway

The overflowing water falls freely and almost vertically on the downstream side of the hydraulic system is classified as a drop spillway. Straight drop spillways are most suitable for thin arch dams, earthen dams or bunds. When the water level in the reservoir rises above the normal pool level, the surplus water falls freely from the crest of the weir and hence it is known as Straight drop spillway or free overfall spillway (Jamal, 2017).

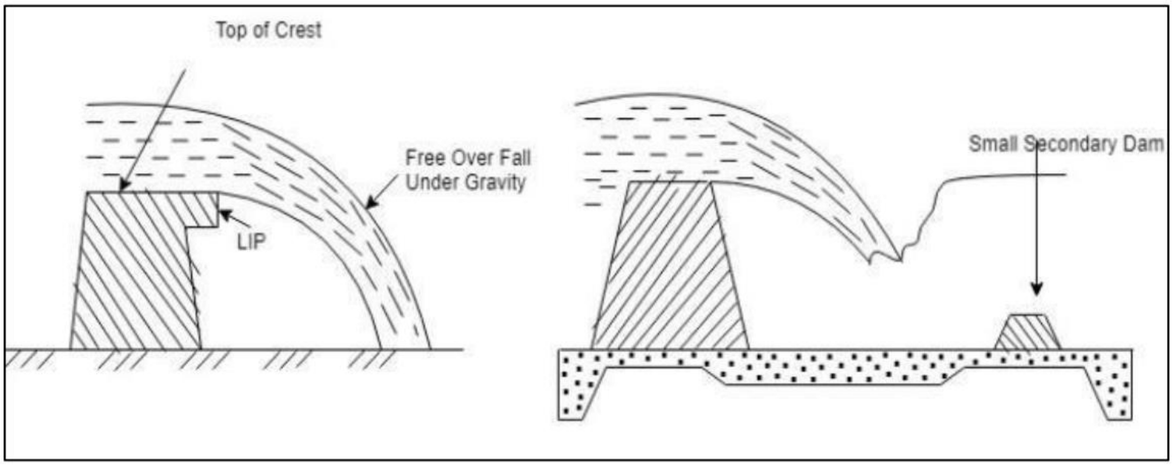

Figure 2.3: Straight Drop Spillway(Kharagpur 2008)

To prevent the scouring of downstream bed from falling water jet, an artificial pool with a concrete apron and low secondary dam is constructed on the downstream side. Proper ventilation should be provided on the underside portion of a falling jet to prevent pulsating and fluctuating effects. Sometimes, an overhanging projection is provided on the crest of the weir to prevent the entrance of small discharges onto the face of the weir wall.

2.3.3 Shaft Spillway

Shaft spillways have a circular crest that directs the flow to an inclined or vertical axis that is connected to a low-grade tunnel (Nohani, 2014). The entrance hole of the vertical shaft is specifically designed in large projects and is known as the morning glory or glory hole of the spillway.

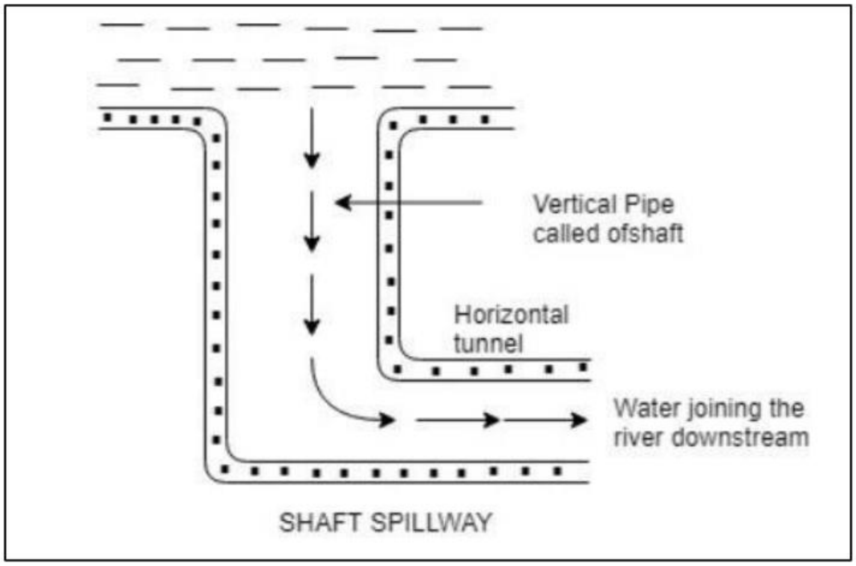

Figure 2.4: Shaft Spillway(Kharagpur 2008)

The excess water enters the vertical shaft, then the horizontal conduit, and ultimately the channel's downstream end. Artificial or natural shafts are used to construct the shaft. Only when the hard-rocky layer on the upstream side is present can the natural shaft be excavated. The horizontal conduit runs either through the dam body or through the dam foundation.

2.3.4 Chute Spillway

The water rushes downstream into a steeply sloped open channel from a chute spillway, which has a brief crest. A baffle block scatters the water in the stilling basin and generates a hydraulic jump to protect the dam's toe from erosion in most chute spillways (Jamal, 2017).

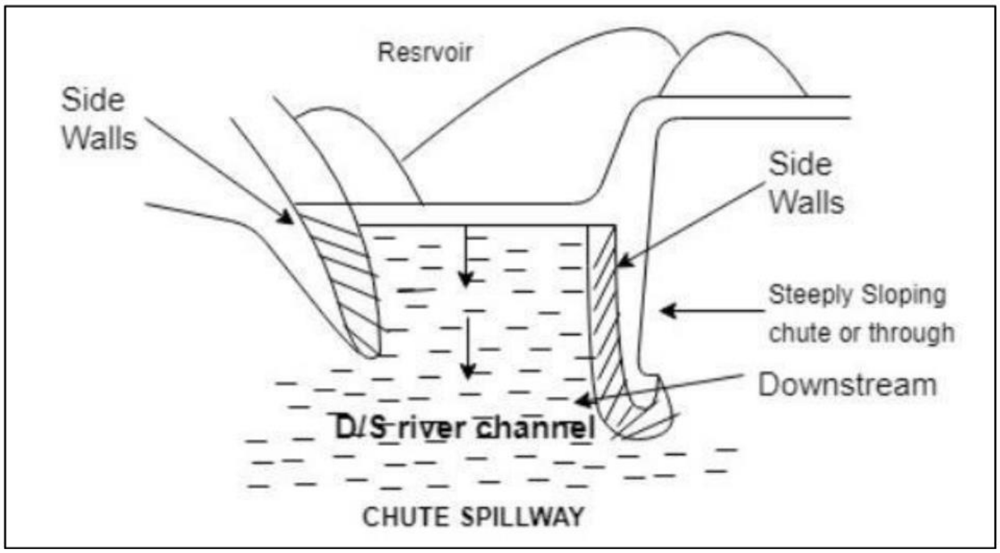

Figure 2.5: Chute Spillway(Kharagpur 2008)

Gravity dams, earthen dams, rockfill dams, and other types of dams can all benefit from a chute spillway. When the width of the river basin is quite narrow, therefore, it is recommended. The water flows downstream of the river, through a steeply inclined chute, trough, or open channel. Trough spillway or open channel spillway are other names for a chute spillway.

2.3.5 Side Channel Spillway

The side channel spillway is a type of hydraulic system that can be employed in a number of different situations. The fundamental difference between side channel spillways and other types of spillways is that the crest of a side channel spillway is usually perpendicular to the dam wall. In other words, unlike a chute spillway, the water pouring from the crest is turned 90 degrees and runs parallel to the crest of a side channel spillway (Jamal, 2017).

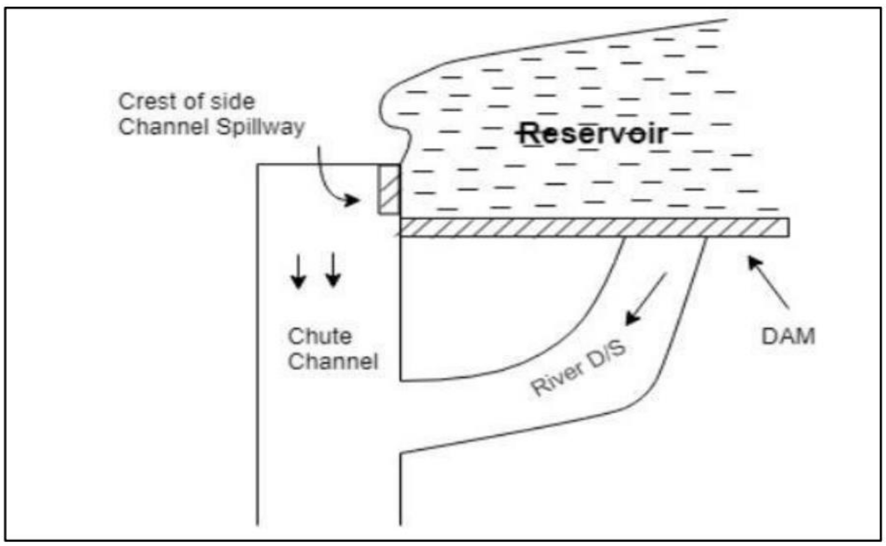

Figure 2.6: Side Channel Spillway(Kharagpur 2008)

When flanks of adequate width are not available, side channel spillways are preferable over chute spillways, usually to prevent extensive cutting. The angle of turn of the water flow after passing over the weir crest can be kept between 0^0 and 90^0 degrees.

2.3.6 Labyrinth spillway

A labyrinth spillway is an overflow weir that has been folded in plan view to produce a greater total effective length for a given overall spillway width. The advantages of a labyrinth spillway over a straight overflow weir and ogee crest.

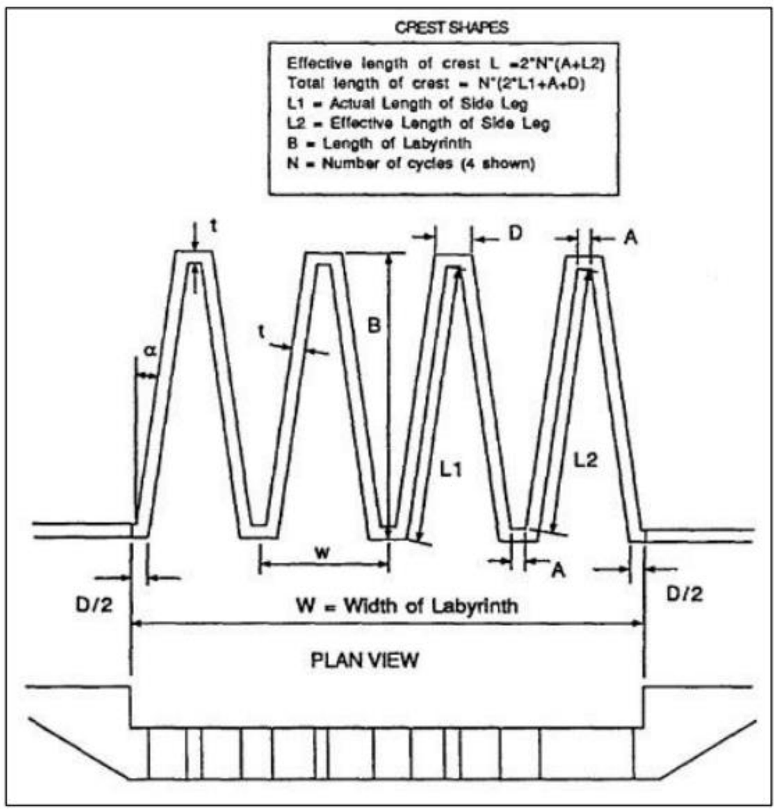

Figure 2.7: Labyrinth Spillway

This increase in effective length increases the weir's discharge capacity, allowing for more water flow at small heads to be easily transported downstream. The length and width of the labyrinth, the crest height, the labyrinth angle, and the number of cycles is the major parameters to consider, while minor parameters like wall thickness, crest form, and apex configuration are also important in designing the labyrinth spillway (Tullis et al. no date)

2.3.7 Importance of spillway

Spillways are important because they have the capacity to operate as flood barriers, and they must be hydraulically sized to guarantee that the flood safely passes through at or below the Probable Maximum Flood (PMF) required (Kamel et al. 2019). It also keeps the tailwater flowing while channeling the extra downstream flow away from the dam and other associated structures.

When a dam's reservoir is full, a spillway allows excess water to flow over or around it. Spillways are critical safety elements for a variety of dams. The erosive force of the water at the foot of the spillway is dispersed away from the foundation by leading over the dam or a portion of it, or via a channel around the dam or a conduit through it (Trojanowski, 2018).

The position or location of the spillway structure is critical for an effective operation that allows the dam to pass the designed flood without overflowing and provides structural integrity during the dam's design life.

The spillway is usually either within the dam construction itself or along the dam's sides. The spillway structures are separated from the dam construction in several places. Furthermore, when the spillway fails to operate due to structural instability, there is a substantial risk of dam failure.

2.4 Flow Induced Vibration Analysis on dam

Due to the effect of flow-induced vibration, dam structures must be evaluated on a frequent basis to ensure their reliability. Vibration induced by the fluid (water) on the dam structure can lead to the catastrophic failure if the natural frequencies coincide with the frequencies of the water flow. The Kenyir Dam's spillway, intake section and also stilling basin are taken into this research. To estimate the dynamic properties of the dam structure, ANSYS software is used to perform modal and harmonic analyses.

Other researchers have undertaken vibration analyses on many types of dams over the years. This research includes a new random vibration formulation developed by Gazetas on 1981 to analyse the dam's dynamic characteristic. In addition, an analytical model can be built to access the relationship between experimental and numerical investigations.

The vibrations of a structure can be studied using a variety of approaches, including ODS and EMA tests. ODS determines a structure's deflection forms under various operating situations, while EMA offers information on the structure's dynamic behaviour, such as natural frequencies and mode shapes (Jenneskens, 2007).

Next, Experimental Modal Analysis (EMA) study is conducted and the Operational Deflection Shapes (ODS) from the effect of low-induced vibration are compared with the natural frequencies. To enhance the dam monitoring process, vibration properties such as natural frequencies, operational frequencies, and deflection shapes must be investigated. Mode shape is the behaviour of the structure at a specific natural frequency, whereas ODS is the vibration response of the structure depending on its operating frequency (McHargue & Richardson 1993).

Figure 2.8: Vibration Analysis measurement points
in Spillway section

Structural vibrations caused by water spilling and surging may have a substantial impact on the dam structure, resulting in a shorter dam lifetime. Despite the fact that this information is crucially significant for dam monitoring, no such study has been published. One strategy for accurately predicting these vibrations is to use a simulation technique called fluid-structure interaction (FSI).

The modelling of a dam should reflect the actual dam construction and behaviour, such as the correlated fluid-structure system, by taking into account the fact that fluid and structure are in direct contact with each other and the entire response of the system is dependent on their interaction.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter discusses the process and procedure that will be used to accomplish the study's objective. This chapter explains the research methods used to validate the physical model of Kenyir Dam in Terengganu. The goals of this study are to study the flow characteristics of the Kenyir Dam Spillway as well as flow induced vibration at the dam. The equipment has been calibrated in order to verify that the data is accurate. All equipment procedures are carried out according to the manual's instructions.

3.2 Study Location of Kenyir Dam Physical Model

The physical model was evaluated at the University Sains Malaysia (USM), Engineering Campus, Pulau Pinang, Malaysia, in the Laboratory of Civil Engineering School.

The mission of creating and testing a hydraulic physical scaled model of the Kenyir Dam was assigned to the School of Civil Engineering. Technicians from the School of Civil Engineering made numerous changes to the model to ensure that it worked properly and that the shape was suitable for testing hydraulic proposals.

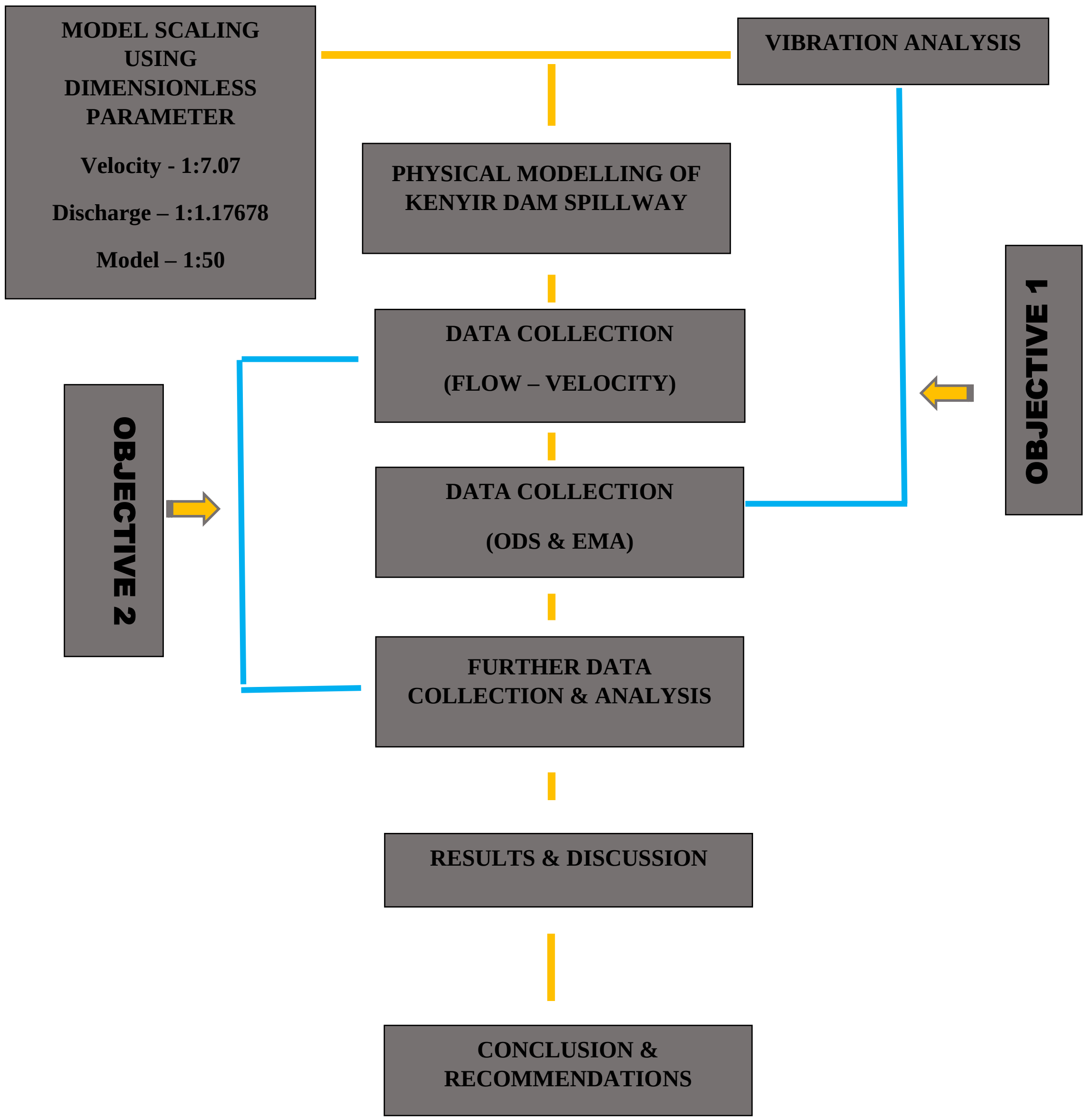

Figure 3.1: Flowchart of overall study

3.3 Physical Model of Kenyir Dam Description

The spillway model was scaled down to 1:50 of the prototype size in order to precisely fit the dimensions of the actual spillway model. The scaled model will be constructed using appropriate construction materials and quality assurance procedures to allow for proportional scaling of the spillway model dimensions in the scaled model. This physical hydraulic model is essential in determining the velocity profile and pressure exerted across the water boundary. Model scaling is the vital factor to consider when designing a physical model. This is because errors in the physical properties of the fluid such as viscosity or surface tension which can have a disproportionately large effect on model efficiency.

The model scaling is the most vital factor to consider when designing a physical model. This is because errors in the physical properties of the fluid such as viscosity or surface tension can have a disproportionately large effect on model efficiency. The appropriate scale was chosen to be 1:50 from the actual size, within this consideration, the physical model is constructed using a fixed-bed model.

Figure 3.2: Physical Model of Kenyir Dam

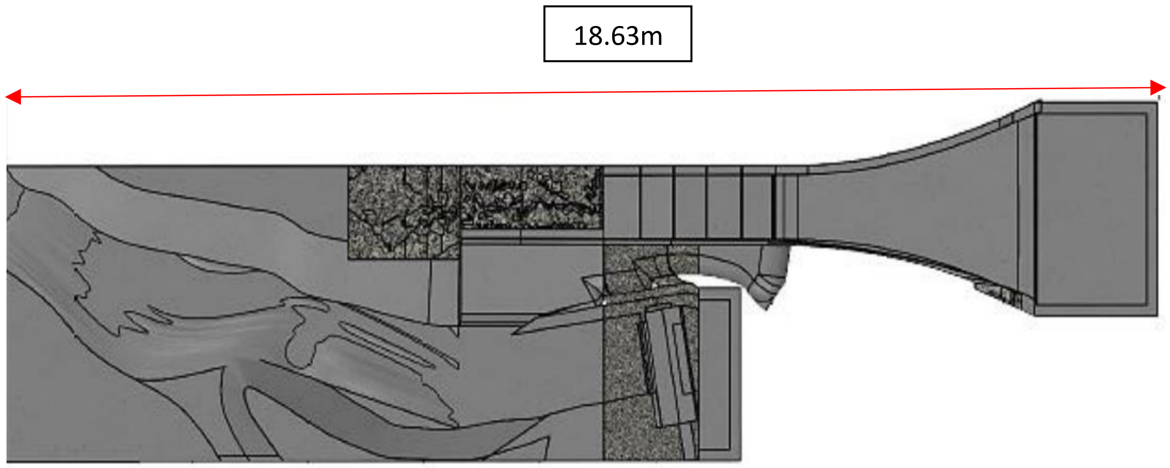

Figure 3.3:Length of proposed Kenyir Dam spillway model

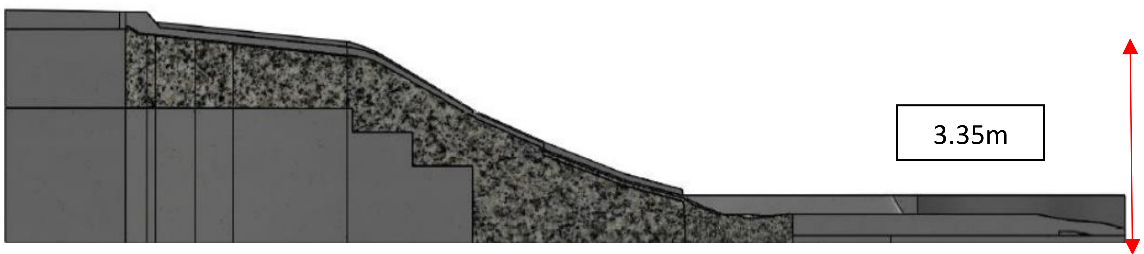

Figure 3.4: Height of proposed Kenyir Dam spillway model

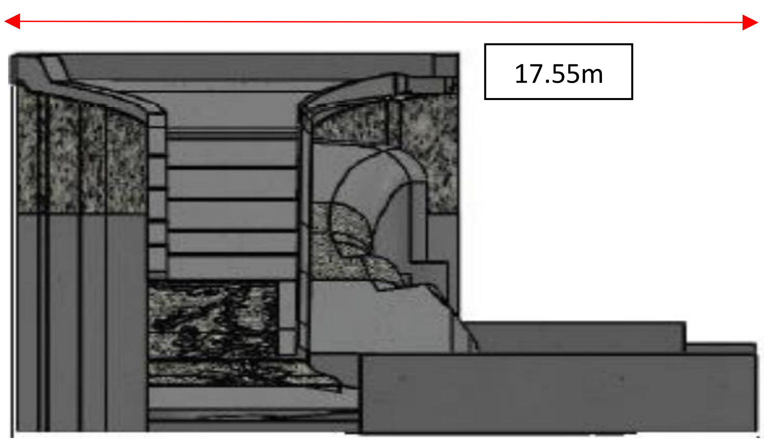

Figure 3.5: Width of proposed Kenyir Dam spillway model

3.4 Equipment

Numerous laboratory equipment has been used to determine the flow discharge, the water surface level, velocity and vibration. It is essential to use the appropriate and effective equipment as the accuracy of the equipment plays a significant role in the analysis parts. Yokogawa Master Flow, Nixon Stream-Flo Velocity Meter and a ruler were all used as part of the equipment.

3.4.1 Doppler Ultrasonic flowmeter

Ultrasonic flow metre is a non-intrusive equipment that use acoustic vibrations to monitor liquid flow rates. To avoid damage or interference with the flow, they must be attached to the pipe's exterior. An ultrasonic beam is sent by a transducer in a Doppler ultrasonic flow metre into the fluid moving through the piping. The flow metre relies on solid particles or air bubbles in the stream to reflect the ultrasonic beam in order to work. The frequency of the beam changes due to particle movement, which is measured by a second transducer.

Furthermore, because the flow metre is not in contact with the liquid, the sensors are not contaminated or degraded. The sensor must be positioned 5 times in a distance between the pipe and the pump to accurately determine the flow. The user-specified parameters, such as pipe ID, units, and pipe wall type, will assist in determining the proper flow discharge.