POTENTIAL FAILURE MODE IN PERGAU SPILLWAY

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POTENTIAL FAILURE MODE IN PERGAU SPILLWAY

by

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LIST OF SYMBOLS

v	Velocity
g	Gravity
h	Free surface level
B	Total height
p	Pressure
p_{atm}	Atmospheric pressure
x, y, z	Distances in Cartesian coordinate
u, v, w	Velocity components (m/s)
t	Time (s)
ρ	Density
K	Cavitation number
pv	Vapor pressure
G_k	Generation of turbulence kinetic energy due to the mean velocity gradients
G_b	Generation of turbulence kinetic energy due to buoyancy
Y_M	Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
σ_k, σ_ε	Turbulent Prandtl numbers for k and ε
S_k, S_ε	User-defined source terms
C_m	Volume fraction function
ρ_m	Density of phase (kg/m^3)
∇	Divergence, gradient operator
N	Shape function
H	Jump function
a_1	Nodal enriched degree of freedom vector
f_a	Asymptotic crack=tip function

b_1^a	Nodal enriched degree of freedom vector
D_0	Substantial or material derivative

LIST OF ABBREVIATIONS

VOF	Volume of Fluid
TNB	Tenaga Nasional Berhad
FSI	Fluid-Structure Interaction
CAD	Computer-aided design
CFD	Computational Fluid Dynamic
FEA	Finite Element Method
XFEM	eXtended Finite Element Method
DIC	Digital image correlation
USM	Universiti Sains Malaysia

LIST OF APPENDICES

MOD POTENSI KEGAGALAN DI PERGAU SPILLWAY

ABSTRAK

Pelbagai mod kegagalan berpotensi dalam bidang struktur hidraulik, memfokuskan pada empangan alur tumpahan, disebabkan oleh air takungan berlebihan, hakisan, dan kestabilan struktur. Dengan masa yang mencukupi, fenomena ini boleh merosakkan permukaan konkrit alur tumpahan pelongsor. Faktor-faktor yang mempengaruhi yang merosakkan alur tumpahan, seperti luahan alur tumpahan, halaju dan tekanan sepanjang alur tumpahan dan geometri alur tumpahan itu sendiri, akan dibincangkan dalam kertas kerja ini. Untuk meramalkan potensi kegagalan dalam alur pelongsor, analisis berangka menggunakan pelbagai teknik berangka dengan perisian yang berbeza dicadangkan. Kertas kerja ini bertujuan untuk mensimulasikan Kesan Paras Air Permukaan Bebas, Peronggaan Aliran Berkelajuan Tinggi, dan Risiko Keretakan akibat Kestabilan Struktur di Limpahan Pergau.

Empat aras takungan berbeza 638.4, 639.4, 640.4 dan 641.08 m persediaan simulasi dilakukan untuk menilai hubungan aras takungan dengan tujuan yang dinyatakan dalam kertas kerja ini. Model CFD 3D disahkan menggunakan data yang diekstrak daripada kajian alur tumpahan. Bagi kajian aras air permukaan percuma, tegasan prinsipal maksimum tertinggi dikira 231910 Pa pada aras takungan 640.4 m dan tegasan prinsipal minimum terendah dikira 159600 Pa pada aras takungan 641.08 m. Ini menunjukkan bahawa tiada jangkaan kegagalan struktur disebabkan oleh kesan paras air permukaan bebas. Bagi peronggaan kajian aliran berkelajuan tinggi, kawasan peronggaan berkurangan daripada aras takungan 638.4m (3508.57 m2) kepada 640.4 m (2183.089 m2), kemudian meningkat sedikit pada 641.08 m

(2674.331 m2). Didapati bahawa pelepasan maksimum tidak secara automatik menyebabkan nombor peronggaan minimum (kawasan nombor peronggaan yang lebih tinggi).

Simulasi berangka yang dicadangkan ini adalah kos efektif dan menjimatkan masa sementara boleh menyampaikan maklumat yang lebih besar tentang kemungkinan mod kegagalan. Kaedah ini lebih sesuai untuk pereka bentuk/jurutera untuk mengoptimumkan model dan reka bentuk alur tumpahan untuk melindungi struktur alur tumpahan daripada sebarang mod kegagalan yang berpotensi sambil mengekalkan kos yang lebih rendah dan menjimatkan masa.

POTENTIAL FAILURE MODE IN PERGAU SPILLWAY

ABSTRACT

Various potential failure modes in the field of hydraulic structure, focussing on the spillway dam, are due to overtopping, erosion, and structural stability. With enough time, these phenomena can damage the concrete surface of a chute spillway. Influencing factors that damage the spillway, such as spillway discharge, velocity and pressure along the spillway and geometry of the spillway itself, will be discussed in this paper. In order to predict these potential failures in a chute spillway, a numerical analysis using various numerical techniques with different software is proposed. This paper aims to simulate the Effect of the Free Surface Water Level, Cavitation of a High-Speed Flow, and Cracking Risk due to Structural Stability on the Pergau Spillway.

Four different reservoir levels of 638.4, 639.4, 640.4 and 641.08 m simulation setup are done to evaluate the relationship of reservoir level with the mentioned purpose of this paper. The 3D CFD model is validated using data extracted from the studies of the spillway. For free surface water level study, highest maximum principal stress is calculated 231910 Pa at reservoir level of 640.4 m and the lowest minimum principal stress is calculated 159600 Pa at reservoir level of 641.08 m. This indicates that there is no expected structural failure due to the free surface water level effect. For cavitation of a high-speed flow study, the cavitation area decreases from reservoir level 638.4m (3508.57 m^2) to 640.4 m (2183.089 m^2), then slightly increases at 641.08 m (2674.331 m^2). It is found that the maximum discharge does not automatically cause the minimum cavitation number (higher area of cavitation number).

This proposed numerical simulation is cost-effective and saves time while can deliver greater information about the potential failure modes. This method is more suitable for the designers/engineer to optimize the spillway model and design to protect the spillway structure from any potential failure mode while retaining lower cost and saving time.

CHAPTER 1

INTRODUCTION

1.1 Overview of Pergau Spillway

The Pergau spillway can be found at the Stesen Janaelektrik Sultan Ismail Petra hydroelectric power station in Kuala Yong, Kelantan, Malaysia. A reinforced concrete slab with an embedded anchor bar is incorporated into the design of the spillway. A flip bucket and area with a plunge pool are located downstream of the spillway. It is a 636-meter-tall stepped spillway model with aerators built into the spillway. Figure 1-1 shows a drone view of the Pergau spillway.

Figure 1-1: Drone View of Pergau Spillway

A spillway is a structure that allows the controlled release of water from a dam, typically into the riverbed of the dammed river. The primary function of the spillways is to prevent water from causing damage to main dam components that are not designed to withstand it. Due to environmental conditions and high-velocity fluid flow on the spillway structure, there are numerous potentials for the spillway to become damaged in sufficient time.

According to General Spillway Design Considerations by the U.S. Department of the Interior Bureau of Reclamation [1], static and hydrologic factors are the most likely causes of spillway failure. Table 1-1 shows the common potential failure mode in the spillway.

Table 1-1: Common Potential Failure Mode in Spillway

Potential Failure Mode	Operation
Static (normal operation)	Internal erosion
	Reinforced concrete structural failure
	Thermo-expansion/contraction
Hydrologic (flood induced)	Dam overtopping
	Stagnation pressure of spillway
	Reinforced concrete structural failure

1.1.1 Overview of the Effect of Free Surface Water Level on Pergau Spillway

This study implements the Volume of Fluid (VOF) method to simulate the free surface flow over the spillway with four different cases of reservoir levels according to the data provided by Tenaga Nasional Berhad (TNB). The analysis of the relationship between reservoir level and spillway discharge is discussed. The numerical results are compared to the data provided by TNB. In addition, the effect of free surface water level of the spillway structure using Fluid-Structure Interaction (FSI) analysis is used to study the deformation, maximum and minimum principal stress of the spillway structure. The relationship between reservoir level and Fluid-Structure Interaction is discussed.

1.1.2 Overview of Cavitation of a High-Speed Flow in a Pergau Spillway

This study applies the hydraulic analytical approach, called cavitation number, to represent the degree of risk of cavitation damage on the spillway structure. Generally, this study considers two important factors influencing cavitation damage: flow velocity and cavitation number. Hence, two different approaches are used: cavitation damage levels based on cavitation number and flow velocity. With this study method, the relationship between different spillway discharges with the area with the highest possibility of cavitation damage can be calculated. Besides, to visualize the computational data, graphs and colored contours illustrating the results related to cavitation number are presented.

1.1.3 Overview of Cracked Concrete on Pergau Spillway

This study discusses the crack propagation on concrete due to hydraulic pressure from the high-velocity water flow on the spillway structure. After the numerical analysis using ANSYS Fluent and Mechanical to study the effect of free water level on the spillway structure, the load applied to the structure is then transferred to ABAQUS to study the crack propagation. An experiment with the three-point flexural test of concrete is done to validate the simulation study. With this method of study, the relationship between the pressure applied to concrete and the length of the crack can be determined.

1.1.4 Overview of Design Improvement on Pergau Spillway

Increases in reservoir water level and flow rate evacuated by the spillway necessitate structural and geometric improvements to the spillway. A pre- and post-modification study will be discussed.

1.2 Software

Dassault Systèmes Solidwork was utilized to design the 3D CAD geometry of the Pergau spillway structure. SpaceClaim was used to create a fluid domain before designing the grids for Mechanical Meshing. FLUENT is used as both the CFD solver and for post-processing. In FLUENT, the VOF method is used to determine the location of the water-air interface. In addition, SIMULIA ABAQUS FEA was utilized to investigate crack propagation using finite element analysis. Besides, ImageJ software is used to measure the area of highest possibility of cavitation damage on spillway chute.

1.3 Problem Statement

There are very limited number of literatures on prediction of chute spillway failure. Generally, it relies on experiment method to observe the measuring factor that damage the structure which are stagnation pressure and high velocity flow. This method is time consuming and expensive. Besides, measuring these factors for the huge dimensions of a spillway structure is challenging. The effect of high velocity flow and stagnation pressure of water flow may destruct the spillway structure due to the cavitation phenomenon. In order to predict the damage risk, the pressure and velocity along the spillway must be studied using the 3D model that represents the Pergau spillway.

1.4 Objectives

By following the stated problem statement, the objectives of the project are planned as follows:

- To study the effect of free surface flow over the spillway with different reservoir level using Fluid-Structure Interaction (FSI) analysis toward the stress and deformation on spillway structure.

- To numerically predict the potential cavitation of a high-speed flow in a Pergau spillway, by combining probabilistic analysis and to study the relationship between different spillway discharge with the area of the highest possibility of cavitation damage, focusing on chute spillway area.
- To study the relationship between hydraulic pressure due to high velocity flow of water and crack length toward the spillway concrete.

1.5 Scope of the project

This study aims to numerically predict the potential cavitation of a high-velocity flow in a Pergau spillway by combining probabilistic analysis with a computational fluid dynamics (CFD) technique utilizing ANSYS Fluent software. By analyzing the cavitation number on the surface of the spillway, the possibility of cavitation damage can be predicted. Using ANSYS Fluent, Fluid-Structure Interaction (FSI) analysis will be used to numerically predict the effect of free surface water level on the structure of the Pergau spillway. Additionally, the objective of this paper is to investigate cracked concrete on the Pergau spillway due to overall stability. Aside from that, it is necessary to provide a vision by enhancing the design of the spillway in order to reduce the possibility of spillway failure. In order to consider a design adjustment, a suggested modification of spillway designs will be prepared.

CHAPTER 2

LITERATURE REVIEW

2.1 Research background

The Oroville Dam spillway incident of 2017 has emphasized the significance of hydroclimatic analysis of dam spillway failure in hydrostatic structures. During flood events, stagnation/uplift pressure and cavitation damage in a chute spillway are possible causes of the incident, based on a summary of 2017 incident characteristics. These are caused by surface irregularities and thermal expansion, and contraction of the concrete of the spillway [1]. Table 2-1 shows the review on spillway dam failure.

The design and maintenance of the spillway must be carefully considered to prevent catastrophic failure. Therefore, it is imperative to take whatever measures are necessary to prevent spillway damage. In this instance, numerical analysis can be used to plan and make numerical predictions regarding the possibility of any associated spillway damage before a failure occurs. In this study, the Pergau spillway in Kuala Yong, Kelantan, was selected as the spillway failure study site.

Table 2-1: Review of Spillway Dam Failure

Review on Spillway Dam Failure	Reason(s)	Detail(s)
Ulley Reservoir and high-velocity spillway flows	Overtopping	The chute walls are being overtopped, eroding the fill behind them and could cause backpressure.[2]
	High flow velocity	The masonry blocks are being pushed out by water pressure from behind as intense turbulence flows through the chute.[2]
Insights into the Oroville Dam 2017 Spillway Incident	Stagnation pressure-related failure	Slab panels that have been lifted. Vertical offsets in joints indicate this condition, which could be caused by poor drainage under slabs and/or insufficient slab anchoring to the foundation.[1]

	Cavitation damage	Cavitation or erosion due to irregularities or a rough surface could be the cause.[1]

2.2 Review on Potential Failure Mode in Hydraulic Structure

This section provides information about previous hydraulic structure failure related to dam and spillway. A case study on the potential failure is investigated.

2.2.1 Teton Dam Failure

Investigations are conducted at Teton Dam to determine the causes of the failure in the construction of earthen dams. The Teton dam failure is shown in Figure 2-1. Theoretically, flood control and hydroelectric power generation were provided by the dam. However, the potential energy of the water reservoir can cause significant damage. According to the report, the dam broke due to internal erosion (piping) of the dam's core in the right foundation key trench, with the eroded soil particles making their way out through channels. Once initiated, leakage rapidly spread through the dam's main body and resulted to its complete collapse [3]. Erosion are basic types of wear in tribology field. Erosion by fluid erosion and cavitation erosion occurs when a liquid is subjected to rapid changes of pressure causing the formation of cavities [4].

Figure 2-1: Teton Dam failure

2.2.2 Cavitation Damage at Oroville Dam Spillway

This study provides a brief introduction and explanation for the problems associated with high velocity flow on spillways near to the chute surface, where the phenomenon occurs. An investigation was conducted at the Oroville Spillway, where it was found that the cavitation damage occurred on the chute spillway surfaces. Figure 2-2 shows cavitation damage occurred on the Oroville spillway surface. From the study, surface irregularities and high speed of water flow are the main factor of cavitation damage [5]. Theoretically, potential cavitation damage can be predicted using cavitation number. The cavitation number or Thoma number is the cavitation index used to estimate cavitation occurrence. A lower index number simply indicates that velocity will be higher, and pressure will be lower, thus creating the conditions for an increased risk [6].

Figure 2-2: Cavitation damage occurred on the Oroville spillway surface

2.3 Simulation and experimental study

This part provides information about earlier numerical work within the field of study, and validation from real spillway structure are compared to numerical work using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) techniques. Additionally, a discussion on experimental study on three-point flexural test are done to validate the agreement on the material properties of the concrete.

2.3.1 Effect of free surface water level on spillway structure using ANSYS

Several academics have previously conducted CFD modelling for free surface flow through spillways. Typically, the objective of these studies is to validate the CFD-model by comparing the flow behavior and jet phenomena to physically scaled models. Previously, a numerical investigation of the flow behavior at the crest of a hydropower spillway was conducted. In the spillway and reservoir, the variables of interest were velocities, water levels, and the shape of the water surface [7].

Free slip and the Volume of Fluid (VOF) method were investigated as for modelling the water-air interaction. The water-air interface is modelled as a ceiling between the two phases using the free slip method. It has been demonstrated that this method is valid if the deformation of the water's surface is less than 10% of the channel depth. Nevertheless, this method is inapplicable if the fluid flow contains surface waves that cause hydraulic jumps [7]. The VOF approach computes the water-to-air ratio for each model cell at each time step. This technique has been demonstrated by previous research to accurately predict hydraulic jumps; hence, it should be utilized in this case [8].

A comparison was made between the standard k-epsilon turbulence model and the more advanced SSG turbulence model. It was determined that the Standard k-e epsilon model and the more advanced SSG model produce comparable average values [9]. In shorts, it was stated that k-e epsilon model can provide comparable result with SSG model with lower computational cost.

2.3.2 Fluid Structure Interaction (FSI) study of the spillway structure using ANSYS

Fluid Structure Interaction (FSI) is the interaction between a deformable structure and an internal or external fluid flow. The fluid exerts pressure loads on the structure, causing its deformation [10]. Concurrently, the fluid geometric domain is modified to account for structural deformations. Simulations of FSI can be categorized as either one-way coupled or two-way coupled.

In one-way coupling, it is assumed that the fluid domain is barely affected by the resulting small structural deformations, so only the fluid pressure is transferred from CFD to the structural domain. In two-way coupling, structural deformation caused by fluid pressure has an effect on the flow field. Every coupling iteration updates the geometry of the fluid domain by exporting pressure from CFD to structural analysis and transferring deformation from structural analysis to CFD [11].

To investigate the deflection frequency of a single-blade pump, a comparison is made between one-way and two-way coupling methods for numerical analysis of fluid-structure interactions. It was demonstrated that, for a simple case, the frequency of deflection was nearly identical for both methods if the vortex shedding frequency was close to the natural frequency [12]. Overall, the one-way coupling algorithm produced reasonable outcomes for specific values in a few instances [12].

2.3.3 Predict the Potential Cavitation of a High-Speed Flow in A Pergau Spillway, By Combining Probabilistic Analysis using ANSYS

Computing cavitation number using ANSYS software has been used to predict the cavitation damage on open spillway structure. The knowledge regarding this matter can help to determine the risk of cavitation damage at predicted places hence maintaining the safety of the structure.

The paper presented by E. Fadaei Kermani present a classification of cavitation damage levels on spillway surface. Flow velocity and cavitation number are two important factors influencing cavitation damage were discussed in this study. The method was applied for Iranian Shahid Abbaspour dam spillway. In short, both flow velocity and the cavitation index factor provide predictions of cavitation damage [13].

Prediction of cavitation damage using cavitation number method has been conducted by Wuyi Wan using computational fluid dynamic (CFD) technique. Using this technique, the potential cavitation region could be visualized using the numerical result, thereby providing more information regarding the potential cavitation region. As part of the simulation process, different ratio coefficients of irregularity, which are 1/20, 1/30, 1/40, and 1/50, are used to correlate it with the cavitation zone. According to the study, a significant irregularity can trigger the occurrence of cavitation and may cause damage to the chute's surface. In short, the larger the irregularity and cavitation zone, the greater the irregularity [14].

2.3.4 Cracking Risk on Hydraulic Structure due to Overall Stability using ABAQUS

A study of cracking risk, overall stability and the reinforcement measures of dam are done by Peng Lin., (2018) at Xulong arch dam. In this study, the analysis of cracking type and cracking factors of the arch dam are done using Finite Element Analysis (FEA) method with ABAQUS. From the analysis, cracks could occur in any possible region of dam concrete blocks before propagating in horizontal or vertical directions [15]. The possible cracking positions of the outlets are depicted in Figure 2-3. According to this study, the change in temperature gradient has a greater effect on the tensile stress and displacement of the arch dam, thereby increasing the risk of dam cracking. Besides, temperature changes, heat from concrete hydration, shrinkage and creep, uncoordinated deformation of dam foundations, earthquake, and seepage effect are the also important causes of cracking [16].

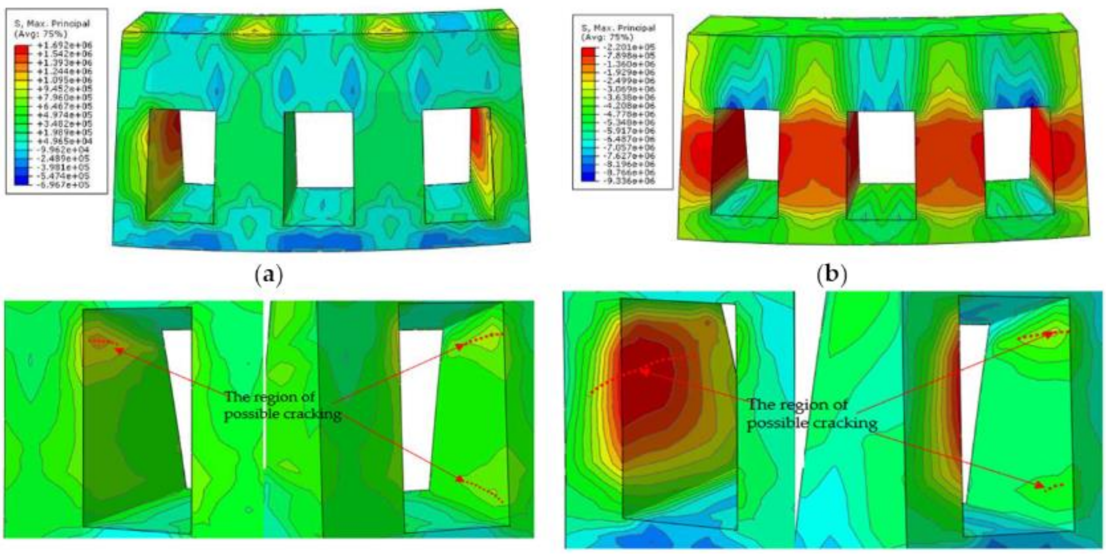


Figure 2-3: Possible cracking positions of the outlets in Xulong arch dam

This paper represents the real instance of the Mequinenza dam, which demonstrates considerable nonrecoverable displacements and cracks. To validate the cracking, a 2D FE simulation with zero-thickness interface parts (Figure 2-4) and a nonlinear constitutive law is performed on the dam. A detailed examination of the cracking on the upstream face was done to locate the probable cracking planes. The modelling considered the self-weight, the hydrostatic pressure, the uplift pressure, and the forced deformation resulting from the concrete's expansion [17].

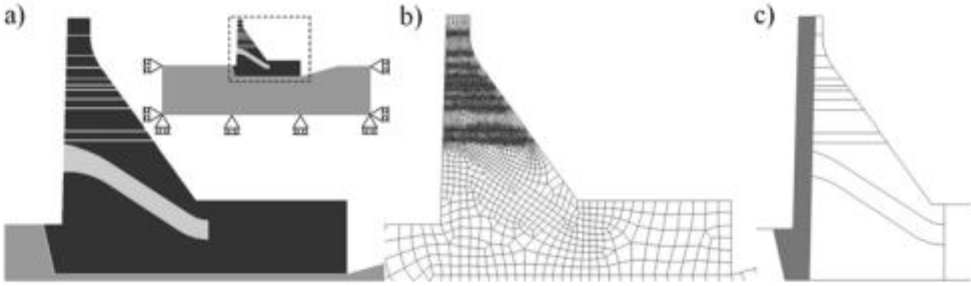


Figure 2-4: 2D FE simulation with zero-thickness interface parts

2.3.5 Three Point Flexural Tests using XFEM Method

In this paper, XFEM numerical simulations were used to simulate the fracture behavior of notched foamed concrete beams with varying densities in three-point bending. In short, XFEM is suitable for describing the fracture behavior of foamed concrete beams in three-point bending, and XFEM-based numerical models and experiments exhibit a good correlation in terms of initial stiffness, peak load, and post-peak behavior [18].

This study compares the flexural wood strength values obtained from three-point and four-point wood bending tests. The correlation between strength and stiffness was higher for the four-point bending test, whereas the correlation between wood strength (MOR) and wood density was higher for the three-point bending test. [19]. This shows that different type of flexural test gives different result of stress and strain properties.

2.3.5(a) Digital Image Correlation

The Digital Image Correlation (DIC) is a powerful contactless tool that provides a full-field measurement of the displacements on the surface of the object of interest, using images acquired at various stages of loading. [20]. In this paper, the DIC are used to measure the deformation, stress, and strain. As a result of this technique, the measurement accuracy is excellent which is approximately 3% of strain. [21].

2.3.5(b) Digital Analysis of Cavitation Number Contour using Imagej

A digital image analysis study is conducted to measure and assess the starch granule shape and mechanical damage of potato starch grains. With the use of ImageJ, it is possible to determine the shape and size of starch granules as shown in Figure 2-5. The software can quickly analyze a large number of micrographs. The findings suggest the possibility of developing inexpensive, user-friendly, and quick automated systems for starch quality control at various processing stages [22].

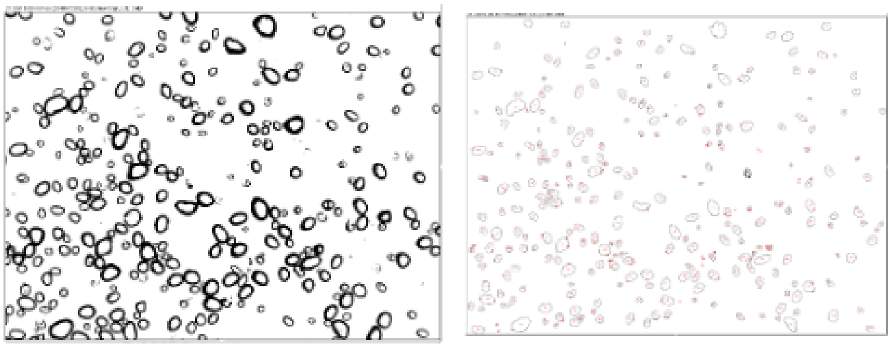


Figure 2-5: Shape and size of starch granules

Using ImageJ software, another digital image analysis study is conducted to evaluate the relative bone density measurement. Several standard operating procedures (SOP) are carried out in order to examine the freehand selection measurement error of a different workgroup member when measuring 10 types of bone region. Overall, the measurements demonstrate consistency, with mean coefficients of variation for intra-individual deviation ranging between 0.194 and 4.402 % [23]. ImageJ, which has been validated in multiple medical analyses, could be recommended, and its incorporation into dental x-ray imaging software is possible.

2.3.6 Summary

There are many potential failures in hydraulic structure discuss in this section especially on the dam and spillway structure. Lessons learned from previous dam and spillway failures should serve as precautions to prevent it from occurring again. Failure such as high-pressure load from water flow, cavitation damage that are caused by high-velocity flow, and cracking risk on the structure can be predicted using simulation software. Simulation work such as Computational Fluid Dynamic (CFD) and Finite Element Analysis (FEA) using ANSYS and ABAQUS software was done to predict the mentioned failure. ANSYS Fluent software are used in determining the dynamic characteristics of spillway such as the pressure and velocity flow in order to study the potential cavitation damage.

In Fluent setup, k-epsilon turbulence model is used for numerical analysis because it can provide comparable result with SSG model with lower computational cost. VOF method are set in Fluent setup, since it can accurately predict hydraulic jumps compare to free-slip method. One-way coupling is used instead of two-way coupling to study the interaction between the spillway structure and fluid flow. The reason is that the time consume are lesser, required lower computational cost, and provide reasonable outcome. In order to predict the cavitation damage, two different methods are done which are by computing flow velocity and cavitation number method along the spillway. With this, the prediction on occurrence of cavitation damage can be done. ABAQUS software are used in evaluating the crack propagation in the spillway. Besides, XFEM method are used to simulate the crack propagation for three-point flexural test simulation and for the prediction on the spillway structure since the numerical models and experiments result exhibit a good correlation in terms of initial stiffness, peak load, and post-peak behaviour.

In three-point flexural test experiment, DIC device are used to measure the deformation, stress, and strain on concrete plate since the accuracy of the measurement is good. To measure the area of cavitation damage from ANSYS CFD-Post, ImageJ software are used. The area can be quickly analysed and measured even the shape and size of tiny particle. Besides, overall measurement from previous study demonstrate consistency with low percentage of error.

CHAPTER 3

METHODOLOGY

3.1 Research topic

In this chapter, numerical setup using mentioned analysis software is used to discuss three main topics (1) the effect of free surface water level of the spillway structure using Fluid-Structure Interaction (FSI) analysis, (2) potential cavitation of a high-speed flow in a spillway, and (3) cracked concrete on spillway due to structural stability will be discussed. A discussion on the expected result is done to visualize the required objective of the study.

The procedure of the three main topics mentioned above will be discussed. Figure 3-1 shows the general procedure for these potential failure mode studies using the stated software. As shown in the figure, the approach includes three primary procedures.

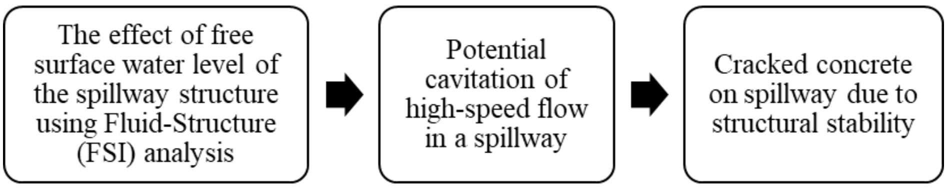


Figure 3-1: General Procedure for Potential Failure Mode in Spillway

3.2 Presentation of Pergau Spillway

The outflow is commanded by a 470 m long and 210 m width concrete gravity ogee weir. A ventilated step is provided at the change in gradient, followed by two further equally spaced steps to aerate the flow and reduce the risk of attack by cavitating eddies adjacent to the concrete invert and walls. An aerator tower is provided on each side of the chute at each aerator step. The chute terminates in a flip bucket with a plunge pool in the existing river channel.

3.2.1 Spillway Properties

The spillway has a maximum discharge rate of 2,403 m3/s, resulting in the flow of the probable maximum flood into the reservoir. Table 3-1 shows the Pergau spillway properties recorded by TNB.

Table 3-1: Pergau Spillway Properties

Type	Height (m)	Length (m)	Discharge capacity (m^3/s)	Type of spillway	Maximum water level (m)	Minimum water level (m)
Concrete G30	644	316	2403	Spillway channel (concrete)	641.08	636.00

3.2.2 Water Properties

The water flow on the spillway is a fresh water with 22 °C with density water of 997 kg/m³. Table 3-2 shows the water properties at Kuala Yong, Kelantan, Malaysia.

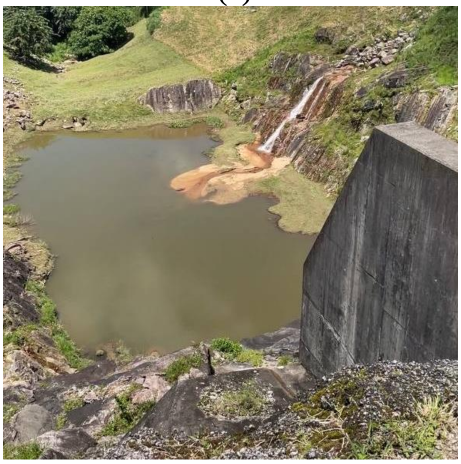
Table 3-2: Pergau Spillway Water Properties

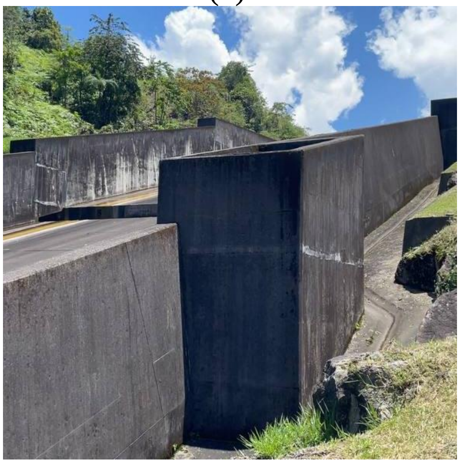
Type	Temperature	Density	Vapour Pressure
Freshwater	22 °C	997 kg/m³	2666.7 Pa

3.2.3 Spillway Character

Pergau spillway includes some common features to provide proper structural stability and help to minimize the possibility of spillway damage due to extremely high hydraulic compression and tensile stress, cavitation damage and uplift pressure toward the chute spillway. The spillway features include (a) Flip bucket (b) Aerator step with perforated pipe (c) Plunge pool (d) Aerator tower. Figure 3-2 shows mentioned features.

(a) (b)





(c) (d)

Figure 3-2: Spillway characters include (a) Flip bucket (b) Aerator step with perforated pipe (c) Plunge pool (d) Aerator tower

3.2.4 Computational Domain

The 3D Pergau spillway structures are done using Solidwork by Dassault Systèmes software, while the free surface hydraulic (fluid domain) are performed with SpaceClaim software. This 3D CAD drawing is done by referring to the drawing of the spillway given by TNB. Figure 3-3 shows the fluid domain along the spillway.

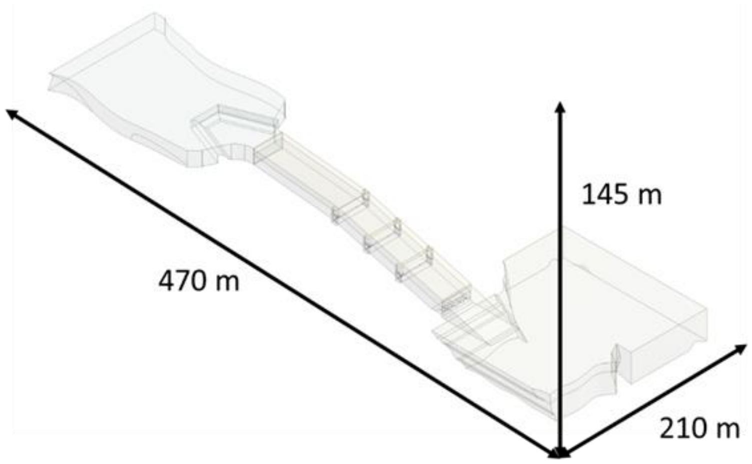


Figure 3-3: Computational Fluid Domain

Figure 3-4 shows the spillway's basic structure, consisting of an aerator tower, aerator step, discharge chute, perforated pipe, and flip bucket. The structure design is really necessary to help the spillway to be long last. Features such as the aerator tower and aerator step really have a significant impact on the spillway concrete. The discharge chute is placed at the height of 636.0 meters above the seawater. The geometry is constructed according to the drawings of the spillway given by TNB.

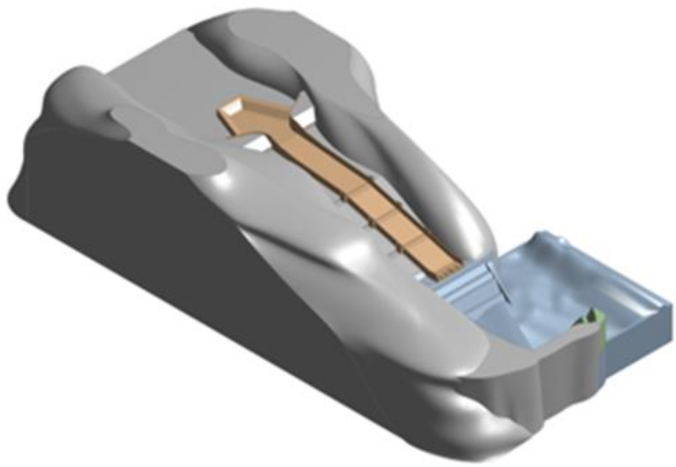


Figure 3-4: Computation Structural Domain

Figures 3-5 and 3-6 show a side-by-side comparison between the drawn spillway and the 3D Pergau spillway.

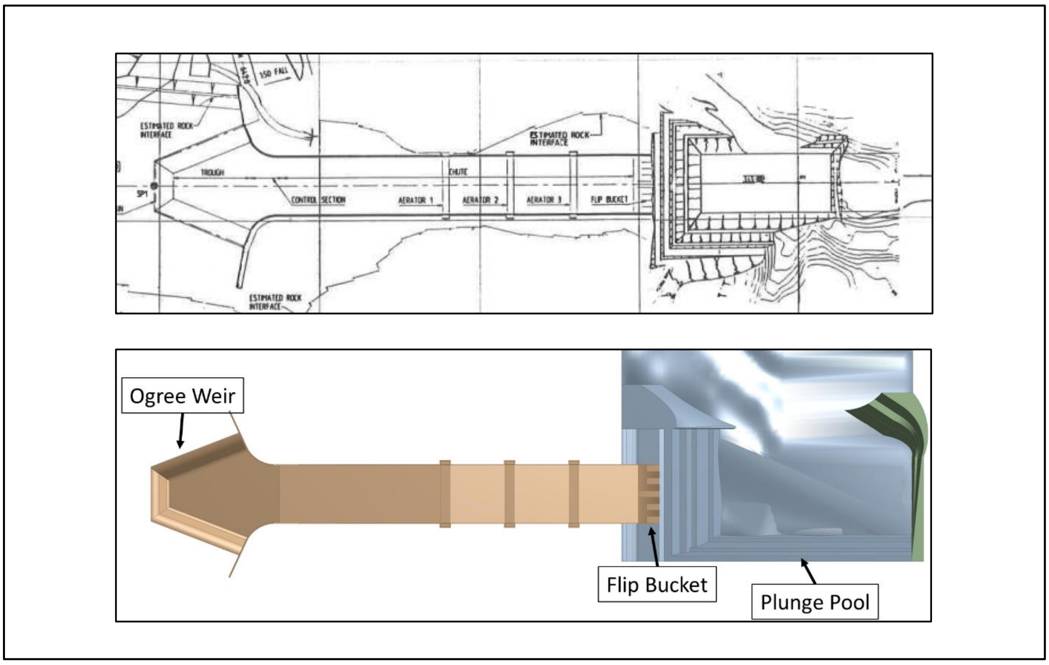


Figure 3-5: Comparison Between Spillway Drawing with Spillway Structural Domain (Top)

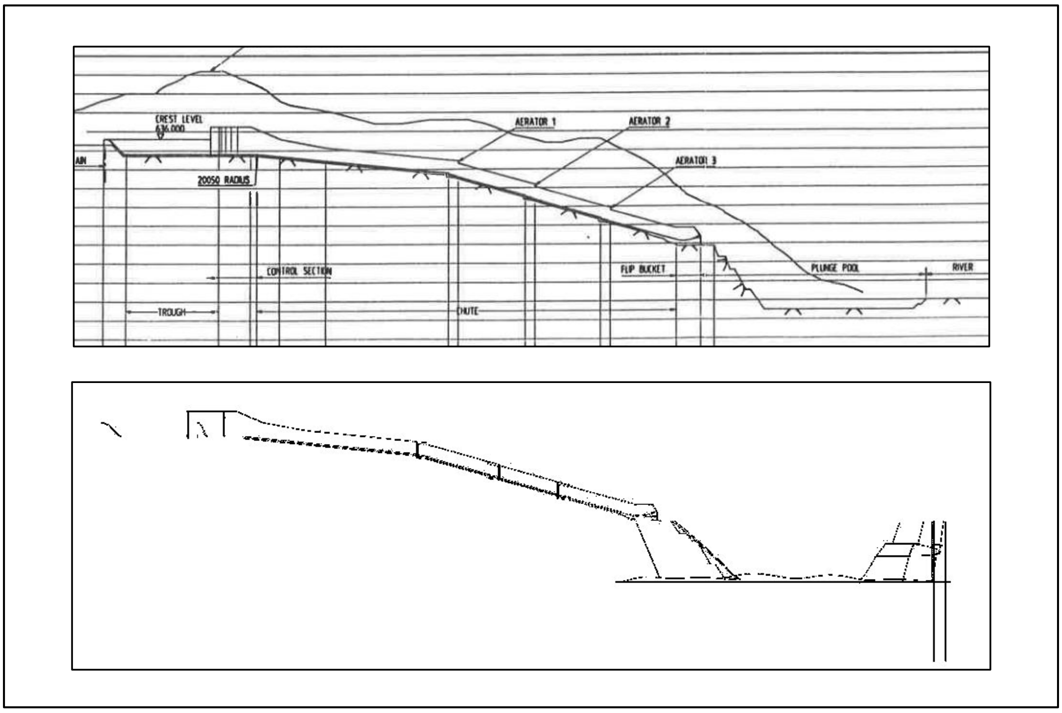


Figure 3-6: Comparison Between Spillway Drawing with Spillway Structural Domain (Side)

Figure 3-7 shows the 3D CAD drawing of the mentioned character on the Pergau spillway.

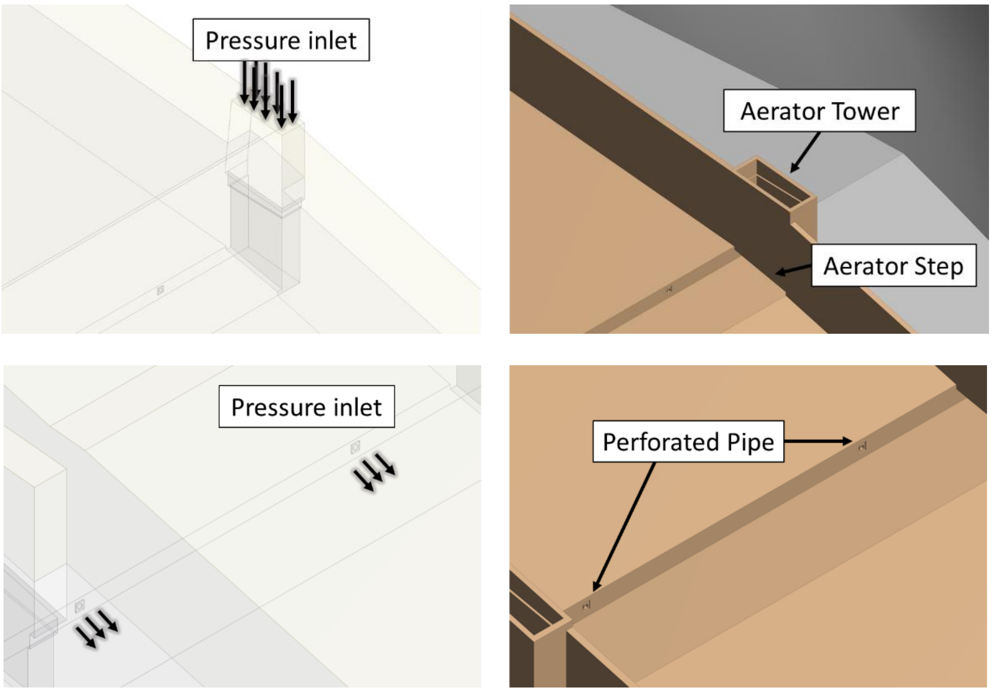


Figure 3-7: 3D CAD drawing on Pergau spillway character

3.3 The Effect of Free Surface Water Level of Pergau Spillway

The spillway has the capacity of discharging 2,403 m^3/s, resulting in probable maximum flood flow into the reservoir. The height of the water level is measured from the head over the weir, as shown in Figure 3-8.

Figure 3-8: Head Over Weir Meter

3.3.1 Numerical Aspect

For the effect of free surface water level of the spillway structure using the Fluid-Structure Interaction (FSI) analysis section, a numerical analysis setup using 3D modelling (Solidwork) and fluid simulation software (ANSYS Fluent) is used to study the effect of free surface flow over the spillway with different reservoir level and to evaluate the deformation, maximum and minimum principal stress of the spillway structure.

3.3.2 Data pre-processing

For the effect of free surface water level of the spillway structure using the Fluid-Structure Interaction (FSI) analysis section, the approach includes five procedures, as shown in Figure 3-9. Firstly, the structural domain is drawn using Solidwork by referring to the 2D drawing prepared by consulting engineering Knight Piesold given by TNB. Then, the drawing is imported to SpaceClaim, as it will be used to draw the fluid domain. Multiphase modelling and volume of fluid (VOF) model are used to simulate the 3D hydraulic characteristic of Pergau Spillway. Then, by using one reference parameter, the average pressure at one setup plane, the value is used to study the model's accuracy. A few simulations setup is prepared.

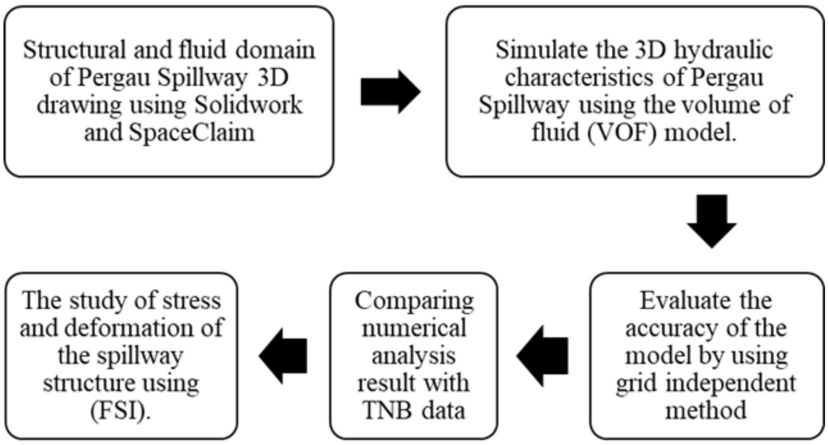


Figure 3-9: Data Pre-Processing for The Effect of Free Surface Water Level of Pergau Spillway Section

After that, the numerical analysis data, focusing on the spillway discharge, are compared with the result from TNB for validation purposes. The result of spillway discharge is plotted. Next, fluid flow data are then imported into Transient Structural.