VIBRATION ANALYSIS OF THE CHENDEROH DAM STRUCTURE DUE TO THE EFFECTS OF WATER SPILLING AND SURGING

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by

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LIST OF SYMBOLS

[C]	Damping matrix
d	Depth of flow
d_g	Degradation index
E	Young modulus
ε	Strain
ϵ	Turbulence dissipation rate
$\{F\}$	Vector of applied force
$\vec{F}$	External body forces
F_r	Froude number
$F(\omega)$	Input force
g	Gravitational acceleration
G_b	Generation of turbulence kinetic energy due to buoyancy
G_k	Generation of turbulent kinetic energy due to mean velocity gradient
$H(\omega)$	Transfer function coefficient
k	Turbulence kinetic energy
[K]	Stiffness matrix
[M]	Mass matrix
$\dot{m}_{qp}$	Mass transfer from phase q to phase p
p	Static pressure
$\rho\vec{g}$	Gravitational body forces
$\bar{\bar{\tau}}$	Stress tensor
$\tau\alpha$	Design life of the structure
u_{max}	Maximum displacement
$\{u\}$	Displacement vector

$\{\dot{u}\}$	Velocity vector
$\{\ddot{u}\}$	Acceleration vector
μ_t	Turbulent viscosity
V	Volume
v	Velocity
ω	Natural frequency
$X(\omega)$	Output deflection
Y_M	Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
λ	Eigenvalues
σ	Stress
σ_ε	Turbulent Prandtl numbers for ε
σ_k	Turbulent Prandtl numbers for k
Ω	Excitation frequency
ϕ	Displacement phase shift

LIST OF ABBREVIATIONS

3-D	Three-dimensional
APDL	ANSYS Parametric Design Language
AVT	Ambient vibration test
BOM	Bill of material
CAD	Computer aided design
DOF	Degree of freedom
DTM	Digital Terrain Model
EMA	Experimental Modal Analysis
FDD	Frequency domain decomposition
FE	Finite element
FEA	Finite element analysis
FFT	Fast fourier transform
FRC	Frequency response curve
FRF	Frequency response function
FSI	Fluid-structure interaction
FVT	Forced vibration test
GVT	Ground vibration test
ODS	Operational Deflection Shape
PolyMAX	Polyreference Modal Analysis Extended
PVC	Polyvinyl Chloride
SAP	Structural Analysis Program
SHEM	Société Hydro-Electrique du Midi
SIMPLE	Semi Implicit Method Linked Equations
SLV	Scanning laser vibrometer
SSI	Soil structure interaction
SVEGM	Spatially varying earthquake ground motion
TNT	Trinitrotoluene
VOF	Volume of fluid
WSEL	Water surface elevation

ANALISIS GETARAN TERHADAP STRUKTUR EMPANGAN CHENDEROH DISEBABKAN OLEH LIMPAHAN DAN LAMPIAS AIR

ABSTRAK

Struktur empangan hendaklah sentiasa diperiksa untuk memantau tahap keselamatan struktur disebabkan oleh kesan gegaran aliran. Gegaran yang disebabkan oleh air boleh menyebabkan kerosakan yang teruk pada struktur empangan jika frekuensi asli bertembung dengan frekuensi aliran air. Dalam kajian ini, kesan limpahan dan lampias air pada Empangan Chenderoh, Malaysia dari segi gegaran akan dikaji. Untuk tujuan ini, hanya bahagian alur limpah dan bahagian pengambilan Empangan Chenderoh yang terlibat. Analisis ragaman dan harmonik telah dijalankan menggunakan perisian ANSYS versi 18.2 (ANSYS 18.2) untuk menentukan ciri-ciri dinamik struktur empangan. Seterusnya, kajian simulasi terhadap interaksi bendalir-struktur (FSI) telah dilakukan dan bentuk pesongan operasi (ODS) daripada kesan gegaran yang disebabkan oleh aliran akan dibandingkan dengan frekuensi semula jadi dan bentuk mod struktur empangan. Berdasarkan hasil kajian, frekuensi semulajadi yang diperoleh untuk bahagian alur limpah dan pengambilan ialah 5.09 dan 2.76 Hz. Analisis FSI menghasilkan frekuensi operasi 4.71 Hz untuk Kes 1 dan 7.45 Hz untuk Kes 2-4 pada bahagian alur limpah. Ini menunjukkan bahawa tiada risiko fenomena resonan berlaku semasa keadaan operasi alur limpah. Fenomena resonan berlaku semasa Kes 3 untuk bahagian pengambilan di mana frekuensi menekan daripada kajian FSI (2.35 Hz) bertembung dengan frekuensi semula jadi bahagian pengambilan. Ini bermakna bahagian pengambilan boleh dianggap tidak selamat untuk keadaan operasi ini. Justeru, prosedur penutupan yang betul untuk kedua-dua pintu air hendaklah dipatuhi untuk mengelakkan segala kerosakan pada struktur.

VIBRATION ANALYSIS OF CHENDEROH DAM STRUCTURE DUE TO THE EFFECTS OF WATER SPILLING AND SURGING

ABSTRACT

Dam structure has to be inspected regularly in order to monitor its reliability due to the effect of flow-induced vibration. 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. In this research, the effects of water spilling and surging to the Malaysian Chenderoh Dam in terms of vibration are studied. For this purpose, only spillway and intake sections of the Chenderoh Dam are taken into consideration. Modal and Harmonic Analyses are carried out using ANSYS software version 18.2 (ANSYS 18.2) to determine the dynamic characteristics of the dam structure. Next, fluid-structure interaction (FSI) simulation study is conducted and the Operational Deflection Shapes (ODS) from the effect of flow-induced vibration are compared with the natural frequencies and mode shapes of the dam structure. From the results, the natural frequencies obtained for spillway and intake sections are 5.09 Hz and 2.76 Hz respectively. The FSI analysis produced the operating frequency of 4.71 Hz for Case 1 and 7.45 Hz for Case 2-4 of spillway section. This indicates that there is no resonance phenomenon during the operating condition of the spillway. However, resonance phenomenon may occurred for the Case 3 of intake section where the forcing frequency from the FSI analysis (2.35 Hz) coincides with the natural frequency of the intake section. This means that the intake is considered unsafe for this operational condition. Thus, a proper closing procedure for both gates should be conducted to avoid any failure to the structure.

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter presents the research background, problem statement, objectives, research contributions, scope of research and the thesis outline.

1.2 Research background

A dam can be defined as a barrier which mostly man-made, and built across the river to stop and control the flow of water. There are various types of dam which function to generate electricity, flood control, navigation, fishing and recreation. In ancient times, dams were used to control the water level and the earliest dam was built in 3000 BC. There are more than 20 dams in Malaysia and one of them is Chenderoh Hydropower Station located in Perak.

The safety of the dam structure can be threatened by the uncertainties of vibration induced from the internal and external sources of the dam structures such as flow of water, earthquake effect, vibration of the hydropower mechanical machine and other related sources. Vibration analysis in the form of experimental modal analysis (EMA) and operational deflection shape (ODS) needs to be carried out in order to test the reliability of the dam structure. The vibration characteristics including the natural frequencies, mode shapes, operating frequencies and deflection shapes need to be studied to aid the monitoring process of the dam. 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 (Richardson & McHargue, 1993; Hammad, 2014).

Analysis on the dynamic characteristics of the dam structures such as Vieux Emosson Dam and North Fork Dam have been conducted over the years and it is discussed in Chapter 2. However, most of the three-dimensional (3-D) models used in the simulation study are overly simplified, which does not represent the actual dam structure. Some researchers even used 2-D models in the simulation study (Iman et al., 2012; Khosravi & Heydari, 2014).

Structural vibrations due to the effects of water spilling and surging may have a significant impact on the dam structure which leads to a reduction in dam lifetime. Although this information is very useful for dam monitoring process, such study has not been reported in the literature. Simulation technique by fluid-structure interaction (FSI) is one of the methods to predict these vibrations realistically. In order to produce a realistic simulation data, the modelling of a dam should reflect the actual dam structure and its behaviour such as the correlated fluid-structure system by considering the fact that fluid and structure are in direct contact with each other and the overall response of the system is dependent on their interaction.

In order to verify the simulation and experimental results, EMA and ODS experiment will be performed on the scaled down physical model of the Chenderoh Dam. The validation will be in terms of mode shape, ODS, natural and operating frequencies.

From the background study of the research, there are three issues that motivated this research:

1) Comprehensive 3-D model that represents the actual dam structure and its behaviour
2) Dynamic characteristics of Chenderoh Dam in terms of mode shape, natural frequency, operating frequency and ODS

3) Vibration analysis on the dam structure due to the effects of water spilling and surging

1.3 Problem statement

Dam operates by allowing water to enter from the main river and at some point discharging back to the downstream river. The flow of water conditions in and out of the dam through the spillway and tunnel can be in the form of spilling and surging. The effects of water spilling from upstream to the downstream area through the spillway and the sudden closing and opening of tunnel gate (for emergency cases) may destruct the dam structure due to the presence of resonance phenomenon. These are the cases that need to be studied for the dam structural reliability.

In order to detect the presence of resonance phenomenon, the vibration characteristics of the Chenderoh dam such as the mode shapes, natural frequencies, operating frequencies and ODS must be investigated in this research using the 3-D model that represents the actual Chenderoh dam.

1.4 Objectives

In this research, three main objectives are set to be achieved:

- To determine the dynamic characteristics of the Chenderoh dam structure (1:1 and 1:20 scale) such as the natural frequencies, mode shapes, operating frequencies and ODS
- To carry out the vibration analysis of the dam structure (1:1 and 1:20 scale) due to the effects of water spilling and surging
- To validate the simulation vibration analysis with the scaled down physical model of the dam

1.5 Research contributions

The findings of this research will contribute the knowledge to the hydroelectric energy and structural safety areas. In terms of structural safety, information on the natural frequency of the dam is very important in order to avoid resonance phenomenon. This is because any vibration that occurs closed to the natural frequency can cause significant damage to the dam structure. The effects of any forced-induced vibration on the dam structure can also be visualized in this research. Aside from the dam, this research work can be applied to study the dynamic characteristics of other structures such as bridge, building and tunnel and this can help prevent unnecessary accidents.

Apart from that, the next contribution of this research is the determination of material degradation effects in terms of mode shape and natural frequency that will assist the responsible parties in monitoring the condition of the structure. Through this research, the effects of opening and closing the gates are studied and based on the results, the Operational Section of Chenderoh Dam can use the results as their references, so that unwanted accidents can be avoided.

1.6 Scope of research

This research focuses on the vibration analysis of the dam structure due to the effect of water spilling and surging. For this reason, only intake and spillway parts of the Chenderoh dam will be investigated and the 3-D model of the real dam is developed. After that, the dam structural material characterization was performed in order to determine the Young Modulus of the concrete material for use in the simulation study. This is based on the compression test that been performed at the School of Civil Engineering, USM.

Simulation study for this research covers the modal and harmonic response analyses to determine the dynamic characteristics of the dam structure and FSI analysis to obtain the ODS and operating frequency using ANSYS 18.2. Then, the relationship between ODS and mode shape are investigated to determine the presence of resonance phenomenon. For the simulation study, spillway and intake are treated as an individual section with proper boundary conditions. After the physical model was constructed, the simulation study was repeated for the 1:20 scale to match the physical model geometry for the validation between simulation and experimental results. However, there are some limitations in this study. Firstly, due to high computational cost, the FSI simulation for each case was conducted for only 5 seconds of running time, which contributes to the limitation of data plot for the frequency response conversion. Secondly, due to lack of information in the original Chenderoh dam drawing, some parts of the dam have to be assumed in term of material that have been used. Finally, for the 1:20 scale, the simulation results are limited to the frequency of 50 Hz.

1.7 Thesis outline

This thesis is divided into five chapters which include:

- Chapter 1 (Introduction), presents the research background, problem statement, objectives, contribution of the research, scope and thesis outline.
- Chapter 2 (Literature review), presents the comprehensive literatures on different types of dam, dam physical model, general vibration analysis on dam, modal and harmonic analysis on dam structure, FSI analysis on dam structure and material degradation of concrete.

- Chapter 3 (Methodology), presents the development of 2D and 3D dam drawings (1:1 and 1:20 scale), dam material characterization, initial validation of dam material, mesh sensitivity analysis, FSI analysis on the dam structure and modal and harmonic analysis of the dam structure
- Chapter 4 (Results and discussions), presents the results of dam material characterization, initial validation of dam material, sensitivity analysis, FSI analysis and modal and harmonic analysis
- Chapter 5 (Conclusion), summarizes the outcomes of the research work and possible future work recommendations.