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Dynamic Analysis of Concrete Gravity Dam Considering Fluid-Structure Interaction

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ABSTRACT: Concrete gravity dams are critical structures that require accurate analysis methods to ensure their safety and performance. The fluid-structure-foundation interaction significantly influences the behavior of dams during seismic events. Analyzing the coupled system of a dam, reservoir, and foundation presents challenges due to the complex interaction among these components. This study aims to assess the static and seismic responses of concrete gravity dams considering fluid-structure interaction, using the Hirakud Dam in Maharashtra, India, as a test model. Three methods are employed to analyze the dynamic behavior of the concrete gravity dam. The first method utilizes a static water pressure approach, considering the hydrostatic forces acting on the dam. The second method applies the procedure outlined in IS:1893-1984, which provides guidelines for calculating hydrodynamic water pressure on the dam during earthquakes. The third method employs finite element analysis to compute the hydrodynamic pressure using the ABAQUS software. In this study, a 3-D Finite Element model is developed using ABAQUS CAE to simulate the coupled system of the dam, reservoir, and foundation. The analysis considers both static and dynamic cases.

KEYWORDS: Concrete gravity dams, Fluid-structure interaction, Static water pressure, Hydrodynamic water pressure, Finite element analysis, Hirakud Dam, Bending moment, Shear stresses, Displacements.

I. INTRODUCTION

India is a vast country with a population of over 1.4 billion people. Water is crucial for the survival of mankind, and for a large country like ours, water resource management plays a very crucial role. Water is not only used for human needs it plays a key role in the production of electricity as in the case of hydroelectric power plants and thermal power plants. Our country is abundant in water resources. We have a very wide and intricate network of rivers our country is surrounded by oceans and is protected by the lofty mountain ranges of the Himalayas. Water management is a very crucial parameter that affects the entire population. As our country receives ample rainfall and the runoff resulting from this rainfall directly impacts our social, geographic, and economic activities, water retaining structures such as dams, barrages, weirs, ponds, etc. play a very significant role in water resource management. Water retaining structures such as dams, barrages, weirs, ponds, etc. together with a water conveyance system consisting of interconnected canals and river system forms the basic structure of our water resource management system.

Concrete dams are crucial structures due to the catastrophic consequences that may result from their failure. As such, it is crucial to subject them to rigorous investigation using precise and logical methods to ensure their safety. One of the primary factors that impact the behavior of dams during earthquake excitations is the interaction between the fluid, structure, and foundation. This is a complex phenomenon that involves the interaction of reservoir water, rock foundations, and concrete dams. Therefore, to design an earthquake-resistant dam, it is crucial to have accurate and dependable analysis procedures that can predict dam response.

II. RELATED WORK

Javanmardi et al. (2005) [1] developed a theoretical method to determine the water pressure variations along a tensile crack during the dynamic response in 2005. The results of the proposed model were compared with experimental test results. It was demonstrated that reservoir water enters the crack and a certain length of the crack becomes partially saturated. Finite element analyses of a 90 meters high gravity dam were conducted. Arabshahi and Lotfi (2008) [2] conducted a study on the natural vibration mechanisms due to damage at the dam foundation interface in 2008. Dynamic stress distribution resulting from the nonlinear response of a concrete gravity dam was investigated with a finite element program developed by the researchers. The local stress space of the interface elements was modeled by a plasticity-based approach. It was demonstrated that a reasonable amount of base sliding decreased the tensile stresses



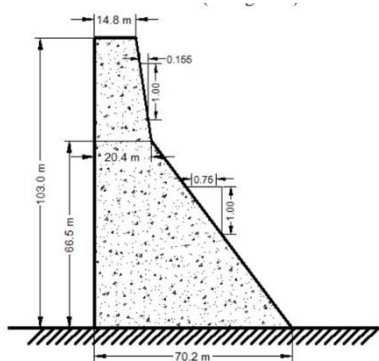
occurring at the dam body, especially at the base. B.A. Zeidan (2013) [3] used ABAQUS CAE code to investigate the interaction of reservoir water dam structure. This system is modeled using Finite Element Method. The time history of hydrodynamic pressure exerted on the upstream face of the dam, horizontal crest displacement and stresses at the dam heel assign significant responses for the coupled fluid-structure system (Zeidan 2013). B.A. Zeidan (2014) [4] effect of foundation flexibility on dam seismic response was analyzed by in 2014 using ABAQUS CAE code. Results indicate that the foundation flexibility has a significant impact on dam seismic response. Maximum displacement and stresses are associated with foundation flexibility ratios EF/EC less than unity, while the least responses are obtained for a very rigid foundation with EF/EC =500. Results assure that in simulating dam-reservoir–foundation interaction problems, the ratio of EF/EC =500 can be recommended to represent the case of fixed foundation with acceptable accuracy.

III. METHODOLOGY

This research uses the underline materials and methods:

Step-1 Model creation: The KOYNA Dam, situated in the Maharashtra State, is part of the KOYNA Hydroelectric Project, which aims to supply water to western Maharashtra as well as hydropower to the neighbouring areas. It is located on the KOYNA River, approximately 193 kilometres SSE of Bombay. The existing KOYNA Dam, completed in 1963, is a rubble concrete gravity dam of 853 lengths and 103 m height. The reservoir has a capacity of 2780×106 m³.

Step-2 Material properties: the material and their properties used in this research are as follows:

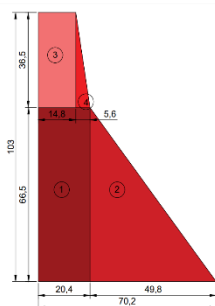


KOYNA dam cross-section

Property	Young’s modulus,	Density, Kg/m ³	Poisson’s ratio	Sonic velocity
Dam Concrete	3.102 ¹⁰ ⁷ kPa	2643 kg/m ³	0.2	NIL
Reservoir Water	2.071 ¹⁰ ⁹ kPa	1000 kg/m ³	NIL	1440 m/s

Material properties

Step-3 Calculations for self-weight and stabilizing moment of the structure:



Self-weight of structure

Section	W(kN)	\bar{x} (m)	M(kNm)	W _s (kN)	M _s (kNm)
1	33790	10.163	343390.8	91331	2018229
2	41459	36.95	1531894.9		
3	13505	7.4	99937		
4	2578	16.68	43006.5		

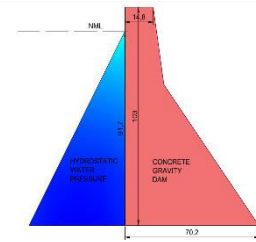
Calculations for self-weight and stabilizing moment

Step-4 Calculation for Static Pressure:

Total Hydrostatic water pressure $P_w = 449.7885$ kN and

Total overturning moment due to hydrostatic pressure (about the toe)

$M_{osp} = 13748.5315$ kNm



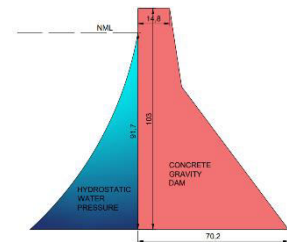
Step-5 Calculation for Hydrodynamic water pressure (As per IS:1893-1984):

The fundamental period of vibration of the dam may be calculated using the equation given in IS:1893-1984 and was found to be 3.06124 seconds. According to average acceleration spectrum table given in IS: 1893-1984 the value of design horizontal seismic coefficient corresponding to a time period of 3.06142 sec is 0.04.

The total hydrodynamic pressure = 121928 N/m

The total overturning moment due to hydrodynamic water pressure (about toe)

$M_{ohp} = 4193$ kN m



Step-6 Calculation for Hydrodynamic water pressure using FEM Analysis: The steps taken in FEM based analysis are as follows:

a) Creation of parts: FEM model consists of the following parts:

PART	MODELLING SPACE	TYPE	GEOMETRY	METHOD
DAM	3D	Deformable	Solid	Extrusion
WATER_DOMAIN	3D	Eulerian	Solid	Extrusion
WATER_REF	3D	Deformable	Solid	Extrusion
BASE	3D	Discrete rigid	Shell	Extrusion

b) Creation of material: This research uses two materials namely water and RCC. The material properties used in this research are as follows:

Property	Young's modulus	Density, Kg/m^3	Poisson's ratio	Sonic velocity
Dam Concrete	3.102×10^7 kPa	2643 kg/m^3	0.2	NIL
Reservoir Water	2.071×10^9 kPa	1000 kg/m^3	NIL	1440 m/s

c) Assembly: In this research, the instances are created from parts created in step-6 (a) and the instance type is dependent (mesh on parts).

d) Step Creation: In this research, two steps for analyses are used namely the initial step and the EQ step. The EQ step contains the parameters necessary for the analysis of dynamic loads. The EQ step is having procedure type general and sub-type general-explicit. The time period used in this research is 10 seconds and the NIgeom feature is set to off.

e) Interaction: For this analysis, the interaction type general contact (explicit) is used under the EQ step created in step-6 (d).

f) Mesh: The mesh size, element type, and total count of elements for each part are given below:

Part	Global Mesh size	Element type	Total
DAM	0.3	C3D8R	11454
WATER_DOMAIN	0.3	EC3D8R	590733
BASE	0.5	R3D4	4300



g) Load: The load cases used in the present research are as follows:

Name	Step	Category	Type	Magnitude
Gravity Load	EQ	Mechanical	Gravity	-9.81(Y-axis)
Euler_Domain	Initial	Other	Material	NA
Static_Pressure	Initial	Mechanical	Geostatic Stress	As per the loading Diagram

h) Boundary Condition: For this research, the boundary parameters are as follows:

Name	Instance	Boundary Type	Step	
			Initial	EQ
DAM	DAM	Encastre	Created	Propagated
Water-Z	WATER DOMAIN	Displacement Z=0	Created	Propagated
BASE	BASE	Displacement All=0	Created	Modified

i) Base Excitation: The earthquake disturbance is applied to the base instance in the form of time vs amplitude format. This excitation is then given to the BASE instance boundary condition created in above steps to simulate the event of the El_Centro earthquake.

j) Job Creation: In this step, we create a job that will be used for the dynamic explicit analysis of the model created in the above steps. Under the parallelization option, we can choose the core count and multiprocessing mode to reduce the analysis time.

k) Results: The maximum moment about the toe is $M_{oFEM} = 38483.26 \text{ kNm @ } 5.24 \text{ seconds (over a time period of 10 seconds)}$

IV. EXPERIMENTAL RESULTS

- a) Stabilizing Moment: The stabilizing moment as calculated by static analysis is 2018229.275 kN m.
- b) Overturning Moment as per Static analysis: The overturning moment as calculated by static analysis is 13748.53 kN m.
- c) Overturning Moment as per Dynamic analysis: The overturning moment as calculated by dynamic analysis is 4192.8 kN m.
- d) Overturning Moment as per FEM analysis: The overturning moment as calculated by FEM analysis is 38483.26 kN m.
- e) Stability against overturning:

Type	Stabilizing Moment	Overturning Moment	FOS
Static	2018229.28	13748.53	147
Dynamic	2018229.28	4192.8	481
FEM	2018229.28	38483.26	52

- f) Maximum Principal Stress due to water-sloshing: The maximum principal stress due to water-sloshing is 25500 kN at the crest.
- g) Maximum displacement due to water-sloshing: The maximum displacement due to water-sloshing is 0.04181 m at the crest in the x-direction.

V. CONCLUSION

The following conclusions are made as per the results observed:

- a) The method given in IS: 1893-1984 for the calculation of hydrodynamic water pressure does not take any consideration of the nature of the earthquake and the related intensity.
- b) The static method only calculates the hydrostatic water pressure acting on the concrete gravity dam.

- c) The FEM analysis using ABAQUS CAE software which uses very complex dynamic explicit analysis methods should be used for complex analyses those involving fluid-structure interaction along with a purely random load.
- d) The results obtained from FEM analysis using ABAQUS CAE are more accurate as compared to analytical equations used in IS:1893-1984.
- e) FEM analysis using ABAQUS CAE can simulate the actual behaviour of fluid-structure interaction using the coupled Eulerian lagrangian method.
- f) The accuracy of FEM-based analysis using ABAQUS CAE is far more than the other techniques but the computational time and the hardware required to carry out such a complex calculation is very high.

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