International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 01, January-2021

# Seismic Failure of Koyna Dam

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***Abstract*—This thesis answers a set of questions relating to the reaction of concrete gravity dams to earthquakes, inspired by the structural damage caused by the December 1967 Koyna earthquake to the Koyna Dam, which has an unconventional cross section. The research is not limited to the Koyna Dam earthquake experience. Still, it involves considering a dam with a normal segment and another earthquake movement of comparable strength. Even, different characteristics of peak acceleration and frequency compared to the ground motion of Koyna. The earthquake reaction is evaluated by the finite element approach in various cases, and findings are presented. Such outcomes add to a range of assumptions. Si. Shake experimental table results of an I/400-scale model of Koyna Dam are presented in this report. Experiments were conducted to simulate a non-overflow monolith's dynamic behaviour due to sinusoidal horizontal base excitations normal to the central dam axis. The excitation frequency value was selected slightly higher than the first in-plane fundamental frequency of the model. The excitation amplitude was increased for each test run until failure occurred at a peak excitation level of 0.16g. The model failure mode closely resembled that observed in the prototype dam. The similitude scaling relations required an innovative material design, one that rose the model modulus of elasticity by the length factor and maintained the prototype material density. The simulated dynamic response provides realistic data for validation and calibration of numerical procedures currently used to model concrete gravity dams' seismic performance. This report describes the experimental results and identifies the dynamic characteristics of the model.**

***Keywords— Seismic failure, Kona dam, prototype.***

## INTRODUCTION

One of the main dams in Maharashtra, India, is the Koyna Dam. It is a rubble-concrete dam built on the river Koyna which rises in Mahabaleshwar, a hill station in the ranges of Sahyadri. It is situated in KoynaNagar, Satara District, on the Chiplunand Karad State Highway, nestled in the Western Ghats. Hydroelectricity, with some drainage in nearby regions, is the primary purpose of the dam. Today, the Koyna Hydroelectric Dam has a gross installed capacity of 1,920 MW and is the largest completed hydroelectric power plant in India. The Koyna River is known as the 'Maharashtra lifeline' because of its electricity generation capacity. The dam plays a critical role in the management of flooding. It is one of the most significant projects commissioned since Indian independence in civil engineering. The Maharashtra State Electricity Board manages the Koyna hydroelectric dam. In the comparative history, the dam has withstood several earthquakes, including the destructive Koynanagar quake of 1967, resulting in some cracks forming in the dam. The grouting of the trials was finished after the tragedy. To ease hydrostatic forces in the body of the dam, internal holes were also drilled. The Indian science establishment has formulated an ambitious proposal to dig a deep borehole in the area and intensively study earthquake activity. This will lead to deeper comprehension and future ear forecast. The request is to drill up to 7km. The physical, geological and chemical processes and properties of the earthquake zone caused by the reservoir are investigated and analysed in real time. It will be a multinational effort to be headed by Indian scientists.[4] The non-overflow part of the dam was upgraded in 1973, followed by the spillway segment strengthened in 2006. It is also predicted that the barrier will be safe from all potential earthquakes, even those of greater severity than 1967 one. State of the art is reviewed in the geological and geophysical study of Koyna and Warna's water reservoir area. The possible geodynamic considerations of induced seismicity are discussed. A complicated trend of the area's structure and recent geodynamics is uncovered by extensive geophysical surveys, satellite geodetic data, and the time history of seismicity in the region. Current data indicate that the seismicity induced here is most likely caused by regional (intra plate) stresses driving the displacements along the orthogonal network of faults whose amplitude has decreased and continues to decline due to the impoundment of the reservoir and activity processes. The evolution of seismicity that began immediately after the rapid filling of the Koyna reservoir in the dam region, then spread rapidly southwards and gradually became concentrated in the Warna reservoir region, indicates that seismic activities can be caused a variety of variables whose contributions which differ over time. The major ones are the filling of the reservoir and its seasonal variations; water saturation of the faults that direct the proliferation of the front of the fracture increased permeability, and potentially mineral transformations (hydrolysis) under the fluctuations of the water level in the reservoirs; and displacement of the front of the hi- Based on the Analysis provided in the report, the recommendations for potential studies to investigate the existence and dynamics of induced seismicity in large water reservoir areas are outlined.

## I. PROBLEM STATEMENT

There is a strong relationship between the earthquakes and loading and unloading of water from the dam. Koyna and Warna region is the world's best site which proves the correlation. Koyna is a unique example globally to study reservoir-induced seismic activity compared to 1,200 big dams worldwide. Around 120 big dams have experienced earthquakes after the water started to get stored at the site. A considerable amount of water stored over the earth's plate can trigger seismic activity in the Koyna region. If the dam fails without warnings, it will be a colossal disaster and causing loss of human life and power as the dam has a vast catchment and generates 60% of Maharashtra state's electricity. The RIS (reservoir induced seismicity) is very serious in the Koyna region as the Koyna dam has built up on a fault plane that tends to move due to loading and unloading of the water in the dam. The construction and presence of dams have already caused many earthquakes resulting in loss of human life.

## II. OBJECTIVE

1. This experimental study's objective was to cast the first 1/400 -scale Koyna Dam model and test it using horizontal shake table sinusoidal motions near the natural frequency of the model. The response of this model is documented in this report and recommendations are made for testing the second mode
2. To find out at which frequency dam model will fail.

## III. METHODOLOGY

- Selection of topic:
  Seismic Analysis of koyna dam‖ we selected this topic because reservoir induced seismicity is a severe problem and koyna dam located in Maharashtra is the best site for the study of RIS (reservoir induced seismicity).

- ·Site visit:
  After we selected the topic, it was essential for us to visit the actual site for koyna for getting a fair idea of the real situation and necessary information and knowledge for initiation of our project we got the permission to visit the dam site from the irrigation department koyna and we saw the dam site on.

- ·Collection of research paper:
  We got the research papers regarding our project from internet research papers that were very helpful for our project's progress.

- ·Analysis of koyna earthquakes:
  For the Analysis of koyna earthquakes we visited MERI (Maharashtra engineering research institute) Nashik, the engineers helped us understand the koyna earthquake. They gave us the seismic data of the koyna region.

- ·Collection of materials:
  After we got the seismic data, it was essential to analyse it. After our Analysis, there was no specific pattern noted in the koyna earthquakes we then collected the information about the dam structure. We took reference of the U.S. Army corps. Research For the design of our dam model.

- ·Casting Model of koyna dam:
  After designing the koyna dam model, we made the formwork of the model using wood for the designed parameters. We fixed the formwork with nails and made sure that it is watertight. Then we filled the M20 grade concrete in the formwork and tamping was done to make sure concrete is evenly distributed in the formwork. After three days the formwork was removed, and curing was done till 28 days under controlled situations.

- Testing of the model:
  The dam model was to be tested for earthquakes, and the tests to be carried out were horizontal shake table test and vertical shake table test.

## IV. MIX DESIGN OF MODEL

### *A. Mix Design for M20 Grade Concrete.*

a. Stipulation for a proportion

| | |
|---|---|
| GRADE CONCRETE | M20 |
| CEMENT | OPC 53 GRADE |
| SIZE OF AGGREGATE | 20 MM |
| MINIMUM CEMENT | 300 KG/M3 |

| | |
|---|---|
| MINIMUM WC RATIO | 0.55 |
| WORKABILITY | 70 MM |
| EXPOSURE CONDITION | MILD |

b. Test data

| Ingredients | Specific gravity |
|---|---|
| Cement | 3.15 |
| Coarse aggregate | 2.74 |
| Fine aggregate | 2.70 |
| Stone dust | 2.94 |

c. Water Absorption

| | |
|---|---|
| Coarse aggregate | 0.5% |
| Fine aggregate | 1.0% |
| Stone dust | 1.2% |

- Target strength for Mix proportioning

Fck1 = target strength at 28 days

Fck = charactaristics compression strength at 28 days

S = standard deviation

Standard deviation, S = 4.0 N/mm2

Fck1 = fck + 1.65 X S

Fck1 = 20 + 1.65 X 4

Fck = 26.6 N/mm2

- Selection of water –cement ratio

From table 5 of IS 456-2000

Maximum water-cement ratio = 0.52

Based on experience water-cement ratio = 0.52

0.52 < 0.55

Hence ok.

- Selection of water content

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 01, January-2021

Maximum water cement for 20mm aggregate = 186 lites [for slump 25 to 50 mm][table 2 of IS 10262]

Estimated water content for 70mm slump = 186 + [[2/100] X 186]= 189.7 liter
= 185 liters

- Calculation of cement content

Water content ratio = 0.52

Cement content = 185/0.52

= 355 kg/m3

From table IS 456-2000,

Minimum water content for mild exposure condition = 300 kg/m3

= 355 kg/m3 > 300 kg/m3

Hence, Ok

Therefore, cement content 350 kg/m3

- Proportion of volume of coarse aggregate and fine aggregate

From table number 3 IS 102662

Coarse aggregate volume equivalent to the aggregate size of 20 mm and fine aggregate for the water/cement ratio

0.50 = 0.60

In % case of water cement ratio = 0.52

Therefore, Volume of coarse aggregate required to be increased to decrease the fine aggregate content.

As water cement ratio is lower by 0.10 %

The proportion of volume of coarse aggregate is increased by 0.02

Therefore, corrected proportion of

Volume of coarse aggregate for water cement = 0.60

Volume of coarse aggregate = 0.60

Volume of fine aggregate = 1 –0.60 = 0.40

- Mix Calculation

The measurement of the blend per unit of concrete volume is as follows.

1. Volume of concrete =1 m3

2. Volume of cement = [(Mass of cement / Specific gravity of cement) X (1/1000)]

= [(350/3.15) X (1/1000)] = 0.111 m3

3. Volume of water = [(mass of water / specific gravity of water) X (1/1000)]

= [(185/1) X (1/1000)]

= 0.185 m3

4. Volume of all in aggregate = 1-(volume of cement + Volume of water)

= 1-(0.111+0.185)

= 0.704 m

5.Mass of coarse aggregate =
(Volume of all in aggregate X Volume Of course X Specific gravity of rough aggregate X 1000)

6.Mass of Fine aggregate =

(Volume of all in aggregate X Volume Of course X Specific gravity of fine aggregate X 1000)

- Mix Proportion

Mix Proportion of Ingredients or 1 M3

| | |
|---|---|
| Cement | 350 kg/m3 |
| Water | 185 kg/m3 |
| Fine aggregate | 760 kg/m3 |
| Coarse aggregate | 1157 kg/m3 |
| Water cement ratio | 0.52 |

- Compaction of concrete:

Concrete compaction is the procedure followed by which the interrupted air is expelled from the concrete. The air in concrete is likely to be interrupted in the course of putting and pouring concrete. In this experiment, if the air is not eliminated, the concrete dramatically loses strength to reach final compaction, and the highest density table vibrator is used.

- Curing of Specimens:

By regular practice, the mortar blocks, beams, concrete blocks & concrete cylinders were fitted. The mortar columns, beams, concrete blocks and cylinder specimens were kept undisturbed 24 hours after planning. Those specimens were removed from the mould after 24 hours and further cured in water. The samples were removed from the water after a particular day and dried for half an hour. The specimens were tested using a compressive measuring machine and a universal testing machine to assess the crushing strength, flexural strength and tensile flexural strength. The full load and force are obtained from the computer, and the result obtained is evaluated and compared with each.

*B. Model Material Properties*

The material properties for the 1/400-scale dam model were defined by us using material scaling relationships. The material properties of the actual Koyna dam and 1/400 scale model design values are shown in Table 1.Both the Koyna Dam and the 1/400 scale model contain no reinforcing steel.

Material Properties

| Material property | Koyna dam | 1/400scale dam model |
|---|---|---|
| Unconfined compressive strength fc | 4000 psi27.6 Mpa | 10 psi 0.069 Mpa |
| Modulus of elasticity E | 4000 ksi<br>27.5 Gpa | Ten ksi<br>0.069 Gpa |
| Ultimate concrete compressive strain Ec | 0.0025 | 0.0025 |

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 01, January-2021

| | | |
|---|---|---|
| Density | 150pcf<br>2403 Kg/m3 | 150pcf<br>2403 Kg/m3 |

## V. EXPERIMENTAL ANALYSIS

### *A. Shake table test*

Koyna Dam Model Test Plan

The test plan's purposes were to evaluate the experimental procedure used to test the first Koyna Dam model and to assure a common understanding of the objectives and progression of all experiments. The test plan defined the test schedule, configuration and instrumentation, and detailed steps to complete all shake table testing.

- Vertical shake table test

| Test name | Starting frequency (HZ) | Ending frequency (HZ) | Duration (MIN) |
|---|---|---|---|
| VST 1 | 1 | 25 | 8.3 |

- Horizontal shake table test

| Test name | Starting frequency (HZ) | Ending frequency (HZ) | Duration (MIN) |
|---|---|---|---|
| HST 1 | 1 | 64 | 10.66 |

## VI. RESULTS

1. Free and forced vibration results for the model were measured to understand the dam's pre-and post-collapse behaviour. The free vibration characteristics of the model were extracted from a shaker-excited modal experiment. Forced dynamic responses included a series of shake-table enthusiastic responses due to sinusoidal excitations and the actual Koyna earthquake record [9]. Additionally, several low-intensity tests were conducted to locate the model's resonant frequencies and validate the modal test results.

2. During vertical shake table testing there was no damage to the dam model. Therefore the dam model is safe against the vertical earthquakes due to the weight of the structure.

3. The dam model experienced cracks and failure at a frequency of 25(Hz). during the horizontal shake table test, the dam may fail if the earthquake waves hit it in the X-direction under the structure.

4. The dam structure is weak at the neck portion as the cracks started developing initially at the neck during the test.

5. This report provides comprehensive documentation of the construction and seismic testing of a 1/400-scale Koyna dam model. The fragile and fluid concrete material presented several unique challenges for formwork construction and testing. The formwork was designed for the Mix's full hydrostatic pressure, but it still leaked significantly during casting. The material also settled significantly, resulting in much more vital, stiffer, and somewhat denser material at the model's base than near the significant fracture surface. The dam developed cracks and a significant crack near the neck of the dam.

## CONCLUSION

The uniqueness of the model presented here over those of the previously investigated experimental ones is due to its inherent capability in reducing simulation distortion (relatively larger size), the use of an innovative material mix meeting the similitude requirements and the availability of complete pre and post-failure data. A creative concrete mix consisting of cement, plastic fibres, barite, sand, and water was designed based on the governing scaling relationships. The dynamic behaviour of the model was extensively documented. The model failed as indicated by the previous field observations, with a crack beginning at the change in slope on its downstream face. The recorded data provide valuable information for numerical models' calibration predicting the seismic response of concrete gravity dams.

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