COMPARATIVE SEISMIC PERFORMANCE OF KOYNA AND CORRA LINN DAMS USING NUMERICAL ANALYSIS AND SHAKE TABLE TESTING

JHORDY RODRÍGUEZ, SAHIL GOYAL, AMIT TIWARI, ANAS SALEM ISSA AND M. SHAHRIA ALAM
School of Engineering, University of British Columbia, Kelowna, BC, Canada

TANZIM ALAM AND ROGER AUSTIN
Cedar Ave., Trail, BC, Canada

JASON TAYLOR7
School of the Arts / ARIC, Selkirk College, Castlegar BC, Canada.

ABSTRACT

Due to the increasing demand for renewable energy resources, there is an increase in the demand for dam construction for the purpose of producing hydropower. India plans to produce 175GW of its power from renewable resources by 2022, including several new dams that are located in highly seismic zones. The seismic performance evaluation of concrete dams has been an extensive area of research specifically after the Koyna Dam incident in India, and various numerical evaluation approaches have been proposed to evaluate the seismic performance of dams such as discrete and smeared crack approach, and the extended and discrete finite element methods. In this study, the performance of the Koyna Dam was evaluated utilizing a scaled finite element model and performing nonlinear time history analysis. The concrete damage plasticity (CDP) model was used to represent the structural behavior as well as the tensile damage development during earthquake loading. Loma Prieta's time history record, scaled to IS 1893 spectrum for zone 4, was implemented for the analysis. The acceleration response and the maximum strains in selected regions were compared with those from a shake table test carried out on a scaled model of the Corra Linn dam in British Columbia, Canada. These results will help refine critical region locations of concrete gravity dams, especially for the Koyna Dam, and the analysis will help identify weaknesses in the design and the viability of seismic performance assessment approaches.

***Keywords**: Seismic analysis, Dam-water-reservoir interaction, Finite element modeling, Koyna Dam, Shake table test, Similitude laws, 3D printing technology, Canada, India*

1. INTRODUCTION

Due to the severe consequences a dam failure can cause downstream, dams are critical infrastructure and justify significant seismic research. The construction of dams involves major financial investments and repairing these structures, once damaged, is a massive and costly undertaking. In the past, dam failures due to earthquakes have caused enormous destruction, including the Shih Kang dam in Taiwan due to the 1999 Chi-Chi earthquake (Charlwood et al., 2000), Hsinfengkiang buttress dam in china during the 1962 Heyuan earthquake (Hu and Liu, 1996) and the Koyna Dam in India during the 1967 Koyna earthquake (Chopra et al., 1973). These conventional examples of damage to concrete result from seismic events, and consequently, the seismic evaluation of dams is necessary for the safe design and operations of dams. Currently, nonlinear time history analysis is one of the best methods to conduct the seismic evaluation of dams.

India is one of the top five dam builders in the world and added 1.9 GW of capacity through hydropower in 2017, the third-largest in the world after China and Brazil (IHA 2018). There are 5745 large dams, with 5334 operating and 411 under construction. Dams have huge economic benefits for India; for example, 47.9 GW of hydroelectricity is produced from them, not to mention flood control, domestic water, and water storage for various purposes including providing irrigation (CWC 2019). Additionally, India is a seismically active country with over 1000 active faults covering 57% of the landmass (Dasgupta et al. 2000). The country has witnessed 650 earthquakes of magnitude greater than 5 on the Richter Scale in the last century, including four great earthquakes of magnitude greater than 8 (Verma et al., 2016). The 2001 Bhuj earthquake (Mw 7.6) resulted in the failure of several earthen dams. According to NRLD (2019), more than 600 dams in India lie in highly seismic zones, with many dams having past their design life, making it essential to economically pre-assess the seismic performance of dams.

The Koyna earthquake is a rare incident of reservoir induced seismicity. The earthquake caused significant cracking at the upstream and downstream faces of non-overflow (NOF) monoliths of the dam and resulted in an increase in leakage through monolith joints. This area of India was considered as a region of low seismicity, whereby the dam was designed for a seismic coefficient of 0.05g but experienced approximately 10 times higher acceleration of 0.49g. The Koyna Dam incident is one of the most researched phenomena and triggered an extensive amount of research to evaluate the seismic performance of concrete gravity dams all over the world. One dimensional (1D) analysis of NOF monolith no. 17, neglecting the effects of the reservoir, was carried out by Chandrasekaran et al. (1969) establishing natural periods and stress concentration regions. Jai Krishna et al. (1970) performed a two-dimensional (2D) static and dynamic analysis, considering the reservoir effect to analyze the section before the earthquake and after a proposed strengthening. Chopra et al. (1973) calculated the natural time periods before and after the strengthening, treating the foundations as fixed and ignoring the reservoir effects. Shake table tests have also been performed to determine the seismic behavior of the dams. Okamoto et al. (1969) carried out a vibration test on the similitude gelatine model of the dam. The influence of the reservoir was considered by adding mass and the natural frequency was computed for monolith 1A and 18 using free vibration testing. Harris et al. (2000) performed shake table testing on 1/50 scale model of the Koyna Dam ignoring the reservoir effects; two models, one with initial shrinkage crack and one monolith were tested to serve as data to calibrate a nonlinear computer model. In addition, it is important to note that, due to the sudden change in the construction schedule to meet the higher power demands, the section shape of the partially constructed Koyna Dam was modified (Mane et al. 1962). This resulted in an unconventional shape for a gravity dam (Chopra et al. 1973) which makes it more difficult to compare the seismic performance of the Koyna Dam with other conventional gravity dams.

This study presents the numerical evaluation method for dams through the Koyna Dam case study. The main objective of this study is to assess and compare the performance of the Koyna Dam in India to that of Corra Linn Dam located in southern British Columbia, Canada. Two scenarios were considered: a non-linear time history analysis was performed utilizing a finite element model of a NOF monolith of the Koyna Dam to identify its seismic performance and the tensile damage development. The acceleration response and the maximum principal strains in selected locations are compared and presented for both dams in this paper. The results of the shake table test and numerical analyses performed on the Corra Linn Dam by Issa et al. (2018) were used for comparison.

2. CASE STUDY : KOYNA DAM

2.1 Description

To evaluate and compare the seismic performance of concrete gravity dams considering the effect of the reservoir, the Koyna Dam has been considered as a case study. It is a rubble-concrete gravity dam constructed in 1963 on the Koyna River in Maharashtra state, India. It is one of the largest dams in Maharashtra at approximately 854 m long (divided in 15.5 m wide monoliths), 85 m high above the river bed, 103 m high above the deepest foundation, about 91.5 m long in the spillway section, and approximately 98.5 m maximum water level capacity above the deepest foundation. Additionally, the criteria adopted for the design of the Koyna Dam was no tension in the section, maximum compressive stresses to be less than the allowable stresses for the concrete used, and the shear friction factor to be less than allowable values (Chopra and Chakrabarti, 1973). The Koyna Dam was also designed for a seismic coefficient of 0.05g, uniform over the height, (Mane and Gupta, 1962). The area was considered as Zone 1 based on the 1967 seismic maps of India (Indian Standards Institution, 1967). Pictures of the Dam are shown in Figure 1 (Koyna Dam, Maharashtra (a); Chopra and Chakrabarti, 1973 (b)).

2.2 Geometry and Material Properties for the Numerical Analysis - Similitude Law Requirements

It is well known that a strong earthquake can push a concrete dam beyond the elastic range, and nonlinear properties of the material and structural discontinuities of the concrete dam must be considered. Adequate simulation of material properties seems to be the most difficult and important consideration for small-scale modeling and testing. Once beyond the elasticity limit of the material, the superposition principle is no longer accepted and it is necessary to reproduce all significant forces that control the behavior up to the structure's failure, which are those due to gravity, earthquake acceleration, and to elastic as well as inelastic deformation (Niwa and Clough, 1980). As a result, for the prototype (real dam) response behavior to be truly reproduced in a model test on a shake table, as well as in the numerical model, Equation 1 is imposed by similitude laws relationships:

$$S_E = S_w * S_L \quad ...(1)$$

[2]M.Eng. student, School of Engineering, University of British Columbia, Kelowna, BC, Canada V1V1V7. E-ma
Sahilgoyal@live.com
[3]M.Eng. student, School of Engineering, University of British Columbia, Kelowna, BC, Canada V1V1V7. E-ma
amit94@mail.ubc.ca
ostdoctoral fellow, EME 3245, School of Engineering, The University of British Columbia, Kelowna, BC, Canad
1V7. E-mail: anasalem@mail.ubc.ca
uctural Engineer-in-Training, 1151 Cedar Ave., Trail, BC, Canada V1R4B8. E-mail: tanzim.alam@austinengine
[6]Principal Dam Safety Engineer, 1151 Cedar Ave., Trail, BC, Canada V1R4B8. E-mail:
roger.austin@austinengineering.ca
structor/Applied Researcher, P100B, School of the Arts / ARIC, Selkirk College, 301 Frank Beinder Way, Castleg
Canada.
[8]Professor, Civil Engineering, EME 4225, School of Engineering, The University of British Columbia, Kelowna,
Canada V1V 1V7. E-mail: shahria.alam@ubc.ca

(a) (b)

Fig. 1 : Koyna Dam: (a) Picture of Koyna Dam (b) Typical NOF monolith section.

Where, S_E is the modulus and strength ratio, S_w is the unit weight ratio and S_L is the length scale. In this study, the length scale was set at 1/250 because this provided a model size that could be conveniently constructed and tested on the shake table available at the University of British Columbia, Okanagan Campus. The geometry of the non-overflow monolith of the Koyna Dam used for this study is illustrated in Figure 2. The upstream wall of the monolith was assumed to be straight and vertical.

The unit weight ratio was fixed to unity because the liquid in the reservoir of both the model and the prototype is water; therefore, the scales for strength and modulus of the model material were taken equal to the length scale and independent of the material density scale (Niwa and Clough, 1980). The tensile strength is estimated to be 10% of the ultimate compressive strength (σ_c=96 96 *kPa*), multiplied by a dynamic amplification factor of 1.25 to account for rate effects; thus, σ_t=12 *kPa* (Lee and Fenves, 1998). It is worth mentioning that, for experimental analysis when the shake table is the excitation system, model materials with suitable Young's modulus are required in order to make the fundamental frequencies of the model lie in the frequency band of the shaking table (Rosca, 2008). The material damping was taken as stiffness proportional Rayleigh damping ($\beta=2\xi/\omega$) to model the energy dissipation arising from deformations, whereas the mass proportional damping (α) was considered negligible (Lee and Fenves, 1998). The materials and scaling factor used for the numerical modeling of the Koyna Dam are presented in Table 1.

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Table 1 : Material properties for Koyna Dam model.

Material	Property	Dam	Scaling Factor Ratio	Model
Concrete	Elastic Modulus (MPa)	31075	1/250	124.3
	Ultimate Compressive Strength (kPa)	24000	1/250	96
	Tensile Strength (kPa)	3000	1/250	12
	Density (kg/m3)	2400	1	2400
	Poisson Ratio	0.2	1	0.2
Foundation	Elastic Modulus (MPa)	27600	1/250	110.4
	Density (kg/m3)	2650	1	2650
	Poisson Ratio	0.33	1	0.33
Water	Bulk Modulus (GPa)	2.07	1	2.07
	Density (kg/m3)	1000	1	1000

2.3 Input Ground Motion

For this study, the Loma Prieta ground motion record was selected to carry out the numerical analysis. It was selected for further comparison with the experimental and numerical studies, where the same record was utilized by Issa et al. (2018). Also, the principal concern was a suitable earthquake simulation of the physical model, capable of providing a structural excitation necessary to obtain an adequate response for this study. The record was matched to the correspondent response spectrum specified in the in the Indian Code IS 1893:2016 considering Soil Type 1 and Zone 4 using SeismoMatch 2020 software (Seismosoft, 2020).This software adjusts any ground motion accelerogram to match a specific response spectrum using a wavelet algorithm proposed by Al atik and Abrahamson, 2010, which results in minor intervention in the frequency content of the records. The matching process was done considering a period range of interest from 0.2T to 2T, where T is the fundamental period of the structure. The properties of Loma Prieta ground motion are shown in Table 2.The response spectrum and the matched time history record are shown in Figure 3.

Table 2 : Properties of earthquake ground motion selected

Event	Year	Record Station	Component	PGA (g)
Loma Prieta	1989	APEEL 10, Skyline	Horizontal	0.367

Figure 3 : Loma Prieta record matching the Indian Design Spectrum.

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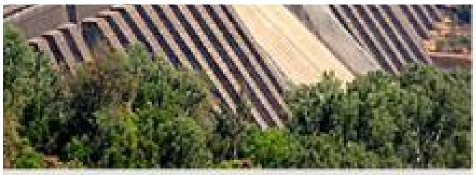
2.4 Modelling of the Dam-Reservoir-Foundation System

To represent the dam-reservoir-foundation interaction, a finite element model (FEM) was created using ABAQUS software (ABAQUS/CAE, 2019). The dynamic response of the dam-reservoir-interaction system is commonly modeled by standard finite elements, where certain assumptions are required to obtain suitable results for the test objective. In some cases, dynamic analyses indicate high stresses which can only be studied using non-linear models (Harris et al., 2000); therefore, in this study, the dam's body was modeled with 4-noded bilinear plane stress quadrilateral (CPE4R) element type and considering a concrete damage plasticity model (CDP) to simulate the behavior of the structure under seismic earthquake excitation.

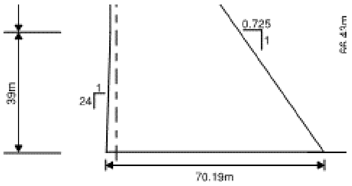
To calibrate the dam with a shake table test scenario, the foundation was modeled as a homogeneous linear elastic structure, neglecting the inertia and damping effects (for a suitable shake table comparison) and utilizing a 4-node bilinear plane stress quadrilateral (CPE4R) element type. To simulate the unbounded nature of the foundation, a coupled non-reflecting finite-infinite (CINPE4) element type was assigned to all boundaries. The contact between the dam and foundation was considered as a no-slip interaction and it was extended to 5 times the dam height in the upstream and downstream direction, and 2.5 times the dam height in the downward direction as recommended in Oberti and Lauletta (1967).

The dam–reservoir dynamic interactions resulting from the transverse component of ground motion can be modeled in a simple form using the Westergaard (1933) added mass technique. The hydrodynamic pressures that the water exerts on the dam during an earthquake are the same as if a certain body of water moves back and forth with the dam while the remaining part of the reservoir is left inactive. This approach was based on the assumption that water is a nonrotating, non-sticky, and a slightly compressible fluid; the reservoir bottom is a rigid plane without energy absorption; the dam body is rigid, and the upstream surface of the dam is vertical. However, in this study, the upstream reservoir was idealized as a finite medium utilizing a 4-node linear acoustic quadrilateral (AC2D4) element type. The reservoir length was taken as 5 times the reservoir depth to consider the damping effect arising from the propagation of pressure waves and the far boundary was assumed to be rigid except for its absorptive capacity (Chopra and Gupta, 1982). The FEM of the Koyna Dam section is shown in Figure 4.

Figure 4 : Finite Element Model of Koyna Dam.



(a)



(b)

Figure 1. Koyna Dam: a) Picture of Koyna Dam b) Typical NOF monolith section.

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known that a strong earthquake can push a concrete dam beyond the elastic range, and r

3. EVALUATION OF THE SEISMIC PERFORMANCE OF KOYNA DAM

In this section, the Koyna Dam is analyzed to determine and further compare its seismic performance. Following the work of other investigators, the non-overflow monolith of the dam is assumed to be under plane stress condition and no interaction with neighboring monoliths. Two scenarios are considered in the analysis:

(1) Earthquake load with the reservoir at 90% of the maximum water level.

(2) Earthquake load with an empty reservoir.

Prior to the earthquake excitation, the dam was subjected to gravity loading due to its self-weight and to the hydrostatic pressure of the reservoir on the upstream wall. Then, in order to validate the finite-element model with the employed assumptions, the first four periods of vibration of the symmetric mode of the dam were determined and compared with those reported in Chandrasekaran (1996), as shown in Table 3. The model accurately matches the natural frequency with an average error of 4.23%.

Table 3 : First 4 natural frequencies of Koyna Dam

Mode	Period of Vibration (sec)		
	Chandrasekaran et al.	Present Work	Error (%)
1	0.318	0.333	4.70
2	0.130	0.126	3.08
3	0.098	0.092	6.10
4	0.066	0.064	3.03

A dynamic analysis was carried out considering only the horizontal components of the ground motion record (Loma Pieta) and applying the load to all the nodes at the base of the dam. The effects of the vertical component of the ground motion were neglected in the simulation to better compare to shake table test results. As identified in the previous experimental studies and in conjunction with the engineering judgment, the downstream and upstream of the dam were instrumented to measure strain and stresses, and the top of the dam was instrumented to measure the acceleration response for each scenario, as shown in Figure 5.

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deformations, whereas the mass proportional d

Figure 5 : Critical stress and acceleration locations selected for the analysis.

The acceleration of the dam at the top obtained from the analysis for both scenarios is shown in Figure 6. It can be seen from this figure that the acceleration with 90% reservoir water level is slightly higher than that in the empty reservoir condition, which, as expected, confirms the transient forces imposed by the reservoir. It was also observed that the acceleration output at the top of the dam was higher than the input acceleration from the record for both scenarios, which can be attributed to the simplification due to the height of the dam. Figures 7 and 8 show the maximum principal strains responses in the selected critical regions. From the figures, it can be observed that the strains on the downstream of the dam are considerably higher (approximately 10 times) than those on the upstream of the dam for both scenarios. The influence of the reservoir can be observed in the increments in both accelerations and strains responses of the structure. Further experimental testing (shake table testing) on the Koyna Dam will supplement these results.

Figure 6 : Acceleration response of Koyna Dam: (a) 90% reservoir water level, (b) Empty reservoir.

Foundation	Density (kg/m3)	2650	1	2650
	Poisson Ratio	0.33	1	0.33
Water	Bulk Modulus (GPa)	2.07	1	2.07
	Density (kg/m3)	1000	1	1000

Input Ground Motion

For this study, the Loma Prieta ground motion record was selected to carry out the numerical analysis. It was selected for further comparison with the experimental and numerical studies, where the same record

Figure 7 : Maximum-Principal-Strain response for 90% reservoir water level at: (a) Downstream of the dam,

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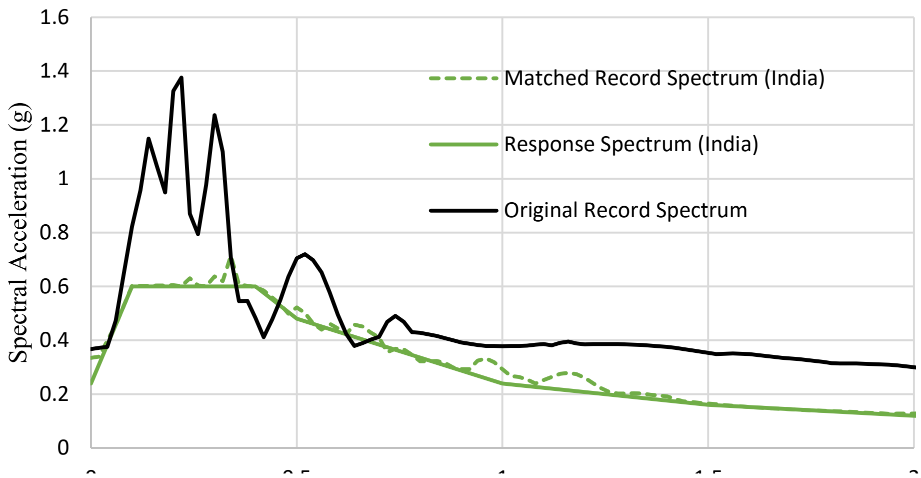
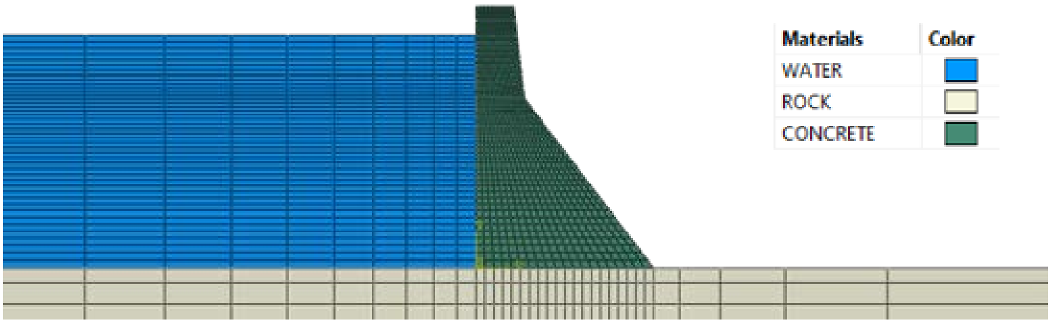
(b) Upstream of the dam.

Figure 8 : Maximum-Principal-Strain response for Empty Reservoir at: (a) Downstream of the dam, (b) Upstream of the dam.



As previously defined, the concrete plasticity model (CDP) was used to represent the behavior of the dam. With this model, the structural damage can be estimated, and the cracking occurrence development process can be reviewed. For such purpose, considering simulate laws, the tensile post-failure behavior was defined in terms of fracture energy cracking criterion by specifying a stress/displacement curve. Similarly, the tensile damage was specified as a function of cracking displacement by using the post-cracking damage displacement curve. These parameters, used to measure the structural damage, are shown in Figure 9. Additionally, the stiffness degradation damage caused by compressive failure of the concrete was taken as zero. All these properties are assumed to be representative of the concrete material in the Koyna Dam and are based on the properties proposed by Lee and Fenves (1998).

Figure 9 : Concrete Tensile Properties: (a) Tension stiffness, (b) Tension damage.



The most critical scenario (90% reservoir water level) was selected to measure the tensile damage development in the dam during the earthquake load, which is illustrated in Figure 10. First, it can be observed that the damage is clearly localized in four zones, one at the heel, one at the upstream and two at the downstream. This data will be utilized to place instrumentation at the locations identified to read the strain responses in the model. The concrete was first cracked almost simultaneously, after 4.554 seconds, at the heel and back of the dam, as depicted in Figure 10(a). The subsequent crack occurred at approximately 5.515 seconds at the front of the dam, as shown in Figure 10(b). This crack propagates to about one-third of the thickness at that level, turns down at approximately a 45 angle to the vertical and keeps going almost until the back of the dam. Similarly, Figure 10(c) shows the last cracking occurrence at 5.918 seconds at approximately one-half of the height of the dam. This crack propagates into the dam to about one-third of the thickness at that level. The final stage of the tensile damage in the dam is illustrated in Figure 10(d).

Figure 10 : Evolution of tensile damage in Koyna Dam

Figure 4. Finite Element Model of Koyna Dam.

:VALUATION OF THE SEISMIC PERFORMANCE OF KOYNA DAM

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4	0.066	0.064

Overall, it can be observed that critical horizontal cracks occurred at the locations in the Koyna Dam, showing poor seismic performance of the dam when subjected to the Loma Prieta record scaled to the correspondent seismic hazard specified by IS 1893: 2016. These results are consistent with those reported in Lee and Fenves (1998). It is worth noting that the Koyna Dam geometry section, which is not typical of concrete gravity dams, and the frequency content of the ground motion record are important variables to consider as they influence the seismic behavior and response of the structure (Chopra and Chackrabarti, 1973).

4. COMPARISON OF KOYNA DAM SEISMIC PERFORMANCE WITH EXPERIMENTAL SHAKE TABLE TESTING OF THE CORRA LINN DAM

As mentioned, the section of Koyna Dam is not typical of concrete gravity dams; therefore, it is of interest to compare its response with other dams when using the same ground motion record. An experimental analysis of a scale-reduced dam was selected to compare their seismic performance in this section.

4.1 Shake Table Test of a Reduce-Scale Canadian Dam (Issa et al., 2018)

In this scenario, a shake table test on a Canadian gravity dam was carried out at the University of British Columbia, Okanagan Campus. The Corra Linn Dam (southern British Columbia, Canada) was selected to experimentally investigate the seismic response of a reduce scaled concrete dam, cast with 3D printed molds, during shake table testing both full and empty reservoir conditions.

For the numerical analysis, a finite element model of the dam was created considering a rigid concrete body with homogenous, isotropic and elastic properties. The reservoir was considered as inviscid and compressible fluid and the foundation was assumed to be massless, considering only the effects of foundation flexibility and neglecting the inertia and damping effects of the foundation rock to calibrate the dam with the shake table test scenario. For the experimental test, a 1:200 scale dam was cast with lightweight, low-strength concrete to reasonably match the natural frequency of the actual dam and satisfy the limits of the shake table test.

Two scenarios were established to carry out the testing, with one having full reservoir capacity (‘full pool’) and one having an empty reservoir (‘empty pool’). Prior to the testing, critical nodes on the downstream and upstream of the model were instrumented to measure accelerations and strains and determine potential damage or cracking during the test. The Loma Prieta earthquake record was scaled to the correspondent design spectrum specified by the Canadian seismic code and utilized in the numerical and experimental testing. The tested specimen is shown in Figure 11.

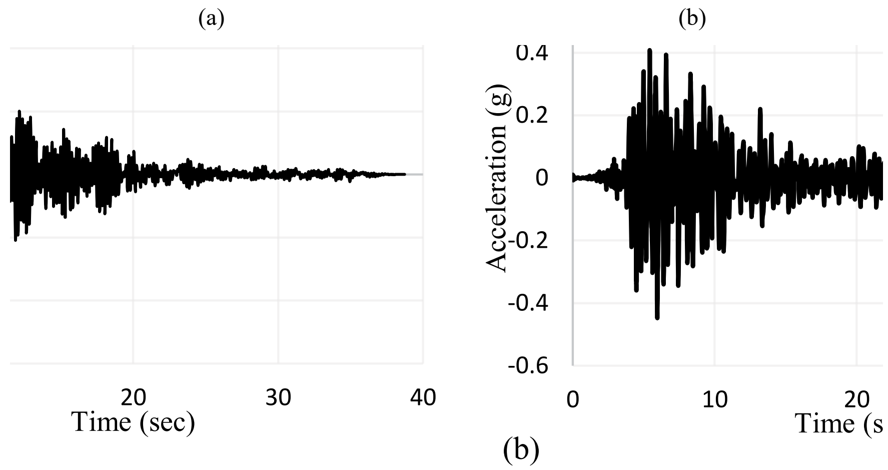
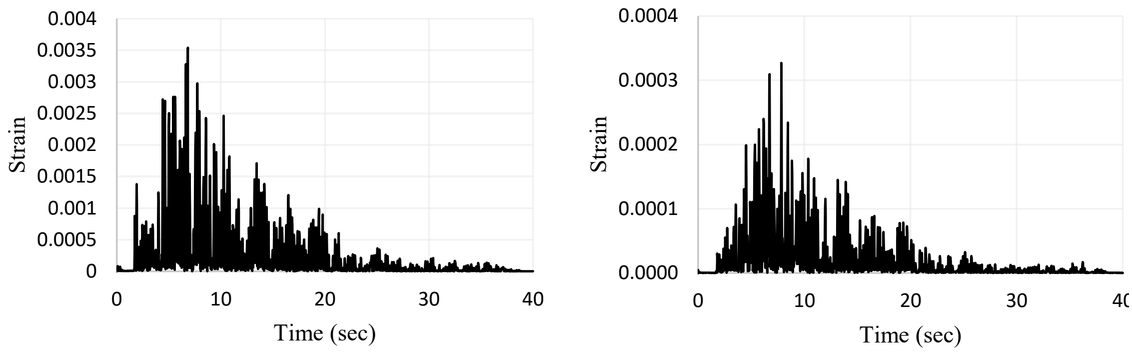


Figure 11: (a) 3D-printed mold and (b) cast model for the Canadian dam.

All the above-mentioned considerations made in the shake table test are consistent with those used in the numerical analysis of the Koyna Dam, which allows for a suitable comparison of the seismic response of both dams. The acceleration response at the top of Corra Linn and Koyna are compared in Figures 12 and 13. Similarly, the strains on the downstream of both dams are compared in Figures 14 and 15, since this location was identified as a critical one.

Figures 12 and 13 show that a full reservoir water level results in a slightly higher acceleration response than an empty reservoir for both dams; however, the acceleration response showed by Koyna Dam is approximately 2.5 times higher than that of Corra Linn dam for both cases. A similar trend can be observed when comparing the strain responses on the downstream of the dam for both scenarios. The strains on the downstream of the Koyna Dam are higher (approximately 3 times) than those in the Corra Linn Dam. The difference in the performance can be attributed to the different seismic areas where the dams are located; the Corra Linn Dam was constructed in a relatively low seismic area, whereas the Koyna Dam was constructed in a seismic area with approximately 3 times higher accelerations and the results correspond well when considering input acceleration.

Figure 12 : Acceleration at the top of the dam for full reservoir: (a) Koyna Dam, (b) Corra Linn Dam.



(a) (b)

Figure 8. Maximum-Principal-Strain response for Empty Reservoir at: (a) Downstream of the dam, (

Figure 13 : Acceleration at the top of the dam for empty reservoir: (a) Koyna Dam, (b) Corra Linn Dam.

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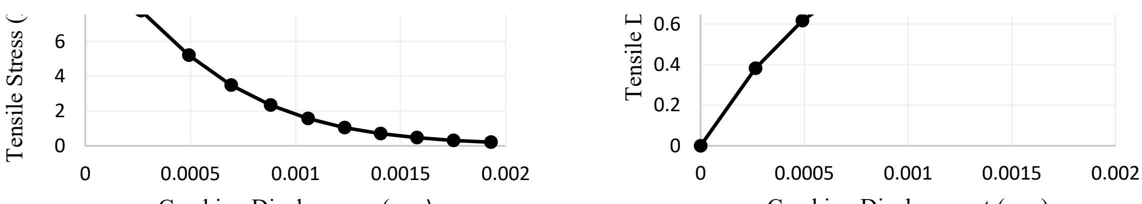
The most critical scenario (90% reservoir water level) was selected to measure the tensile damag development in the dam during the earthquake load, which is illustrated in Figure 10. First, it can t

Figure 14 : Strain response on the downstream of the dam for full reservoir: (a) Koyna Dam, (b) Corra Linn Dam.

)verall, it can be observed that critical horizontal cracks occurred at the locations in the Koyna Dam 1owing poor seismic performance of the dam when subjected to the Loma Prieta record scaled to th(orrespondent seismic hazard specified by IS 1893: 2016. These results are consistent with those reporte(1 Lee and Fenves (1998). It is worth noting that the Koyna Dam geometry section, which is not typica f concrete gravity dams, and the frequency content of the ground motion record are important variable:) consider as they influence the seismic behavior and response of the structure (Chopra an('hackrabarti, 1973).

Figure 15 : Strain response on the downstream of the dam for empty reservoir: (a) Koyna Dam, (b) Corra Linn Dam.



(b)

Figure 9. Concrete Tensile Properties: (a) Tension stiffness, (b) Tension damage.

5. SUMMARY AND CONCLUSIONS

To analyze and compare the seismic behavior of a scaled gravity dam, the Koyna Dam was considered as a case study. A finite element model was created to carry out a numerical analysis to find out the structural behavior under earthquake loading considering full and empty reservoir conditions.

Accelerations at the top of the dam and strains in selected critical locations were analyzed and compared with experimental shake table tests carried out on a Canadian dam. The analysis with full and empty reservoir conditions confirmed the transient forces imposed by the reservoir. Both, full and empty reservoir conditions were analyzed. The Koyna Dam showed a poor seismic performance mainly due to the much larger seismic action the structure was subjected to that lead to considerable damage; however, the model demonstrated that the cracking on the gravity dam did not extend through the entire structure and thus the dam is still likely to retain the reservoir following the selected seismic event.

Although considerable progress has been achieved and reported in the literature, more research works are required to improve the reliability of the seismic design and safety evaluation of concrete dams with new and improved economic techniques. Based on the results of this investigation, we conclude that shake table testing of reduced scaled dams utilizing 3D printing modeling technology is a powerful approach that allows suitable conditions for laboratory testing and further comparison with numerical analysis. Scale model testing provides invaluable insights into the analysis of earthquake response and failure mechanisms of concrete gravity dams which are more important in terms of climate change to support capital planning and improve dam safety throughout the world.

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