Structural Behavior of Two Major Concrete Dams in Sri Lanka Under Earthquake Loads

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ABSTRACT

Dams are built for a variety of purposes including hydropower generation, irrigation, water supply, and flood mitigation. Concrete and earth dams are common types of dams in Sri Lanka. Concrete dams can be categorized as Gravity dams and Arch dams. Gravity dams are most common in Sri Lanka. Dams can also pose safety hazards. Failure of a dam can cause serious damages to both people and property downstream. One of the major threats to dams is earthquakes. They can have significant impacts on the stresses within the dams. In extreme cases this can cause even failures of dams. These possibilities can be investigated using finite element analysis.

In this study Rantambe and Moragahakanda concrete gravity dams were selected for 2-D finite element analysis under the action of suitable earthquakes. For each case linear time history analysis was performed using SAP2000 software. The stresses were examined for potential failures. Important considerations in this process were selection of dams, selection of suitable earthquake records, and identification of an appropriate failure criterion. The selection of earthquake records was based on proximity and geological conditions. Koyna earthquake was used to develop suitable earthquake loadings. Peak ground acceleration was varied from 0.05g to 0.15g. Westergaard method was used to assign hydrodynamic loads. Coulomb-Mohr criterion was employed to investigate potential failures in concrete.

Stresses in dam models during the earthquakes was scrutinized for potential failures. Significant stress increases were observed in some areas of the dams. These critical areas and corresponding values of earthquake parameters were identified. It was concluded that the dams were unlikely to suffer material failures under earthquake loads even with a peak ground acceleration of 0.1g (which is the value recommended for use for critical structures in the areas concerned).

KEYWORDS: *Concrete gravity dams, Finite element model, Coulomb-Mohr criterion, Time history analysis, Westergaard method*

1 INTRODUCTION

Sri Lanka is situated in the Indo-Australian tectonic plate but far away from the plate boundaries. So it is considering a non-seismic country. Past records indicate only a few minor earthquake events in the country. Earthquakes can be defined as sudden slips or sudden movements on earth surface in the tectonic plates of the earth's crust. (Bolt, 2021)

Sudden movement of earth surface creates inertia forces in structures. This may cause variations in structural responses such as stresses. Such increased stresses may pose hazards for the safety of structures such as high-rise buildings and dams. Potential dam failures might imply threats perhaps even more significant than building failures. If a dam fails under an earthquake it can cause serious damages to properties and people in downstream areas. This is a situation that has much relevance to Sri Lanka.

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Sri Lanka has more than 350 medium and large dams. (Samarajiva, Goswami, and Ennen, 2006). There are two main types of dams in Sri Lanka: concrete dams and earth and rockfill dams. Concrete dams have been used more frequently for medium and large dams in modern times due to some advantages such as cost effectiveness, feasibility of large heights and of large reservoir capacities. Arch type and gravity type are the two main types of concrete dams found in Sri Lanka. Most of them are gravity dams. Therefore, it is important to examine the risks for gravity dams under earthquakes.

Analysis of a dam's structural response to earthquake loads is important to identify potential threats to the dam. This can be conveniently done using finite element method which is a computerized procedure for structural analysis under static and dynamic loads. (Ghanaat, 2004). In 2017 Karunananda and Tharmarajah performed a seismic analysis of Victoria arch dam in Sri Lanka using SAP 2000 finite element software package.

Response Spectrum analysis and time history analysis are the two main methods for finite element analysis of dams under seismic loads. They involve a few main steps such as preparing finite element model, assigning loads and boundary conditions, analyzing, and interpretation of results. (Yaghin, and Hesari, 2008)

2D or 3D finite element models can be used for analysis. Long and straight concrete gravity dams with approximately uniform cross-sections can usually be analyzed satisfactorily with 2-D finite-element models. But curved arch dams require 3-D models. (Ghanaat, 2004).

An earthquake load can be applied to a finite element model as a time history function to represent loads varying with time. Static analysis methods are not suitable for these seismic loads. (Salamon, 2015). Ground acceleration and frequency are the most important parameters in an earthquake. Time history analysis can be done for dams using acceleration records that reflect these earthquake parameters.

Water pressure on a dam during an earthquake also should be considered. Westergaard has proposed a method to determine the hydrodynamic pressure of the water on an upstream vertical side of a concrete dam during an earthquake event. (Zhou et al., 2017). Approximate form of Westergaard equation is normally used for calculating hydrodynamic loads in finite element analysis. The approximate form is a convenient way to calculate hydro dynamic forces, and results are not much different from what is obtained using the actual Westergaard equation. (Salamon, 2015)

Strictly speaking, for an accurate analysis the foundation (usually rock) on which the dam sits also should be included in the finite element model. However, it has been shown that, if the ratio of the elastic modulus of foundation material to that of the material of the dam body is high, foundation does not significantly influence the structural behavior of the dam. In such cases the dam foundation need not be included in the finite element model. Instead, the dam body can be treated as fixed at its interface with the foundation. (Zeidan, 2015)

In order to assess the likelihood of material failure in a dam under seismic loads it becomes necessary to use a failure criterion for the dam material which is usually concrete. Concrete is a brittle material. There are a few failure criteria for identifying material failure in concrete. Coulomb-Mohr criterion and Drucker-Prager criterion are good for identifying failure of concrete in linear time history analysis. (Malm, 2016).

In the present work structural behaviors under earthquake loads of two important concrete gravity dams in Sri Lanka was examined. Time-history analysis using SAP2000 finite element package was performed for each of the two dams under appropriate seismic loads and the results were examined for potential material failure in the dams.

2 METHODOLOGY

2.1 Selection of two dams

Rantambe and Moragahakanda concrete gravity dams were selected for this study. This was mainly based on consequences of failure and safety considerations. Selected dams are located in hilly areas which would be affected more severely in the event of an earthquake near Sri Lanka. The presence of large populations downstream of each dam amplifies the severity of consequences to life and property in the case of a potential failure of the dams.

2.2 Selection of an earthquake parameters

There are no detailed past records of any major earthquakes in close proximity to Sri Lanka. This necessitates the use of earthquake records form other locations or the use of synthetic earthquake records. For the present study the former approach was adopted

Koyna earthquake (M 6.3) recodes were selected for the analysis. It had happened in Maharashtra in India in 1967 (Figure 1), This area also is located on the Indo-Australian tectonic plate. Most of topographical conditions of Koyna area are similar to Sri Lankan topographical conditions. Another advantage is that detailed and accurate data are available for Koyna earthquake. In the PEER data base SEISMOSIGNAL software was used to scale earthquake records to correspond to different peak ground acceleration values.

Figure 1. Locations of Koyna earthquake

The blue color lines in Figure 1 show tectonic plate boundaries near Sri Lanka and the Koyna earthquake location

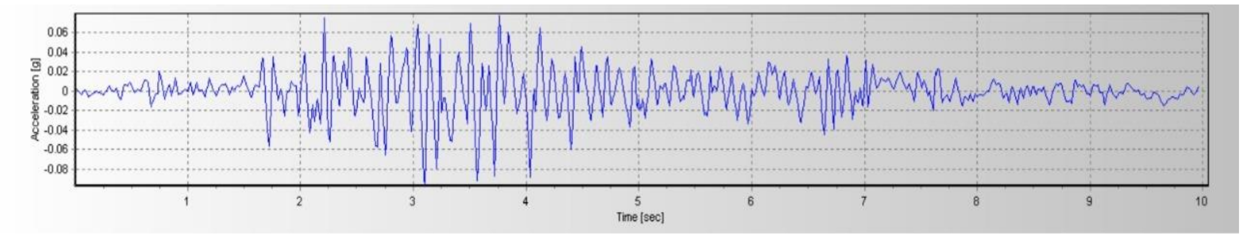


Figure 2. Seismograph of Koyna earthquake (PGA 0.1g)

The Koyna earthquake duration is 10s and each time period is 0. 01s.Therefore the time history record consists of 1000 time steps.

2.3 Dimensions and material parameters.

Table1. Important dam dimensions

Dimension	Rantambe Dam	Moragahakanda dam
Height (m)	39	55.2
Crest width (m)	5	8

Details of the dam configuration for finite element modelling was obtained from the Mahaweli Authority. Sections with the highest value of body height were selected for each dam. The relevant dimensions are given in Table 1. As material parameters, tensile strength was estimated following IS 456-2000.

$$\text{Tensile strength (MPa)} = 0.7\sqrt{f_{ck}} \quad (1)$$

$$\text{Modulus of elasticity (MPa)} = 5000\sqrt{f_{ck}} \quad (2)$$

where f_{ck} = Compressive strength of concrete (MPa)

Compressive strength of concrete in Rantambe dam is 15 MPa and Moragahakanda dam has concrete of two different compressive strengths – 15 MPa and 20 MPa. (Figure 3).

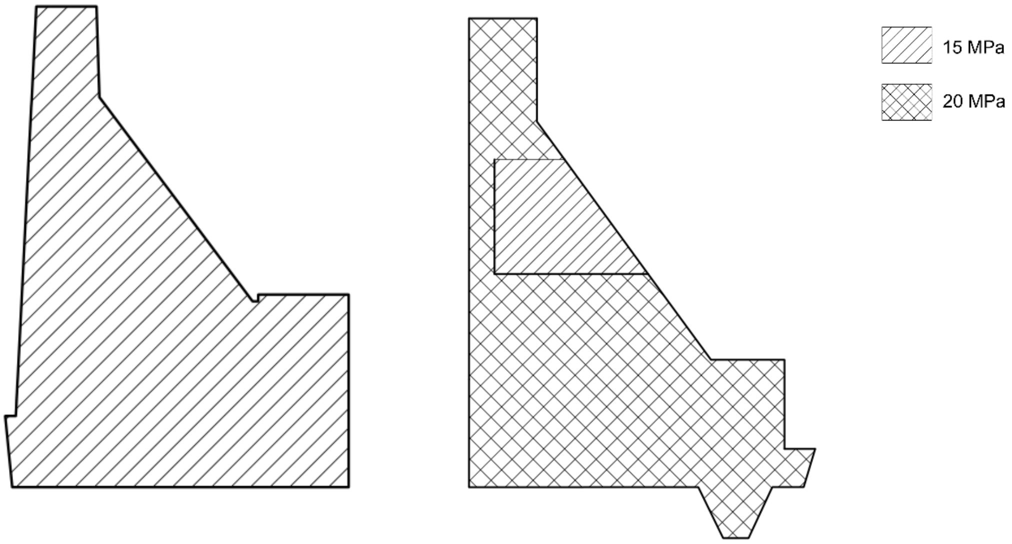


Figure 3- Compressive strengths of concrete layers on dams
(Left: Rantambe, Right: Moragahakanda.)

2.4 2D finite element models of the dams

The axes of both Rantambe and Moragahakanda dams are straight. Their cross-sections are also approximately uniform. Therefore, 2D finite element models were adequate for reasonably accurate results. (Ghanaat,2004). 2D finite element models were developed for the two dams using SAP2000. Quadrilateral elements were used in each mesh. All elements were developed with aspect ratio close to one and the meshes were refined to check convergence of results. Foundations of the dams were assumed to be much stiffer than the dams and not included in the models. Fixed boundary conditions were applied on the dams at their interfaces with the foundations. The two models are shown in Figures 4 and 5.

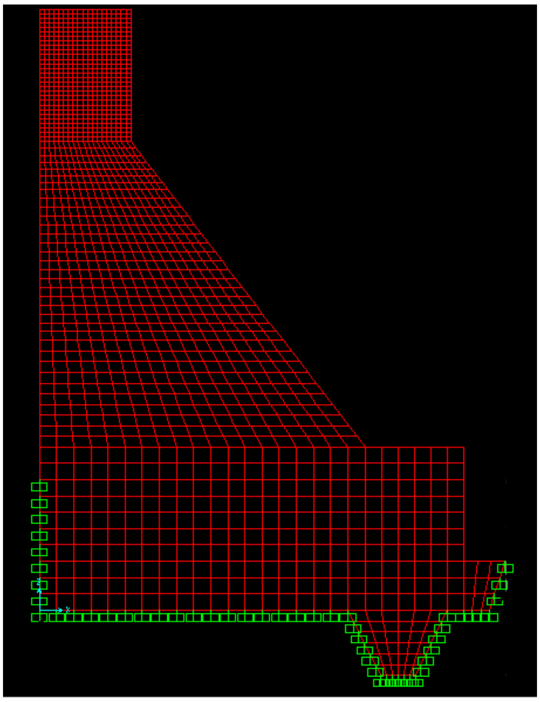


Figure 4. 2D Model of Moragahakanda dam

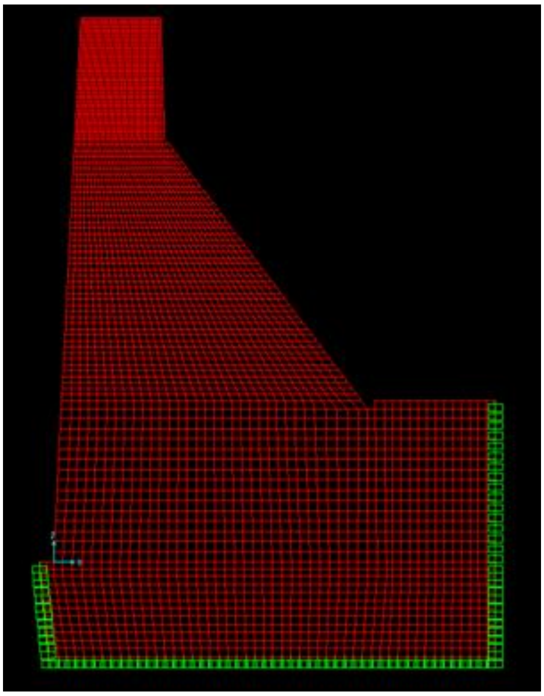
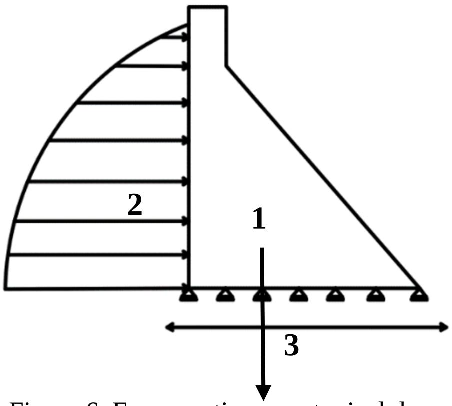


Figure 5. 2D Model of Rantambe dam

2.5 Assigning boundary conditions and loading



1 = Self weight of dam.
2 = Westergaard hydrodynamic pressure.
3 = Earthquake loads

Figure 6. Forces acting on a typical dam

Earthquake load was applied as a time history function. Koyna earthquake parameters were used and analysis was done by changing peak ground acceleration values as 0.05g, 0.1g and 0.15g. The possibility of an earthquake happening in Sri Lanka is low. So, these moderate peak ground acceleration values were used (Seneverathne et al, 2020)

Westergaard hydrodynamic load was assigned as hydrodynamic pressures acting on the dams under an earthquake event. The following Westergaard approximate equation was used for this purpose. (Salamon, 2015)

$$P_d=0.875\ W_0.\ k\sqrt{(H.h)} \tag{3}$$

P_d = Westergaard hydrodynamic pressure.
W_0 = Unit weight of the water (kN/m).
k = Design seismic coefficient. (0.1).
H = Height from reservoir water surface to the foundation level (m)
h = Depth from water surface to calculated point (m)

Several assumptions had been used to derive Westergaard equation. Reservoir was assumed to contain water to maximum capacity and dam's upstream surface was considered as Vertical. Loads were applied to each node on the upstream side of the dam.

2.6 Failure criterion

To represent the brittle behavior of concrete, Coulomb- Mohr failure criterion was used to examine the failures of the material under earthquake loads. In terms of the principal stresses σ_1 and σ_3, Coulomb - Mohr criteria can be defined as shown below. The corresponding failure curve is illustrated in Figure 7.

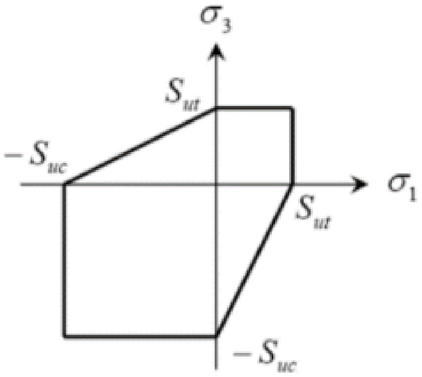


Figure 7. Coulomb-Mohr failure plane

$(\sigma_1 / S_{ut}) \leq 1$; if $0 \leq \sigma_1 \leq \sigma_3$. (4)
$(\sigma_1 / S_{ut}) - (\sigma_3 / S_{ut}) \leq 1$; if $\sigma_3 \leq 0 \leq \sigma_1$. (5)
$(\sigma_3 / -S_{uc}) \leq 1$; if $\sigma_3 \leq \sigma_1 \leq 0$. (6)

S_{uc} = Compressive strength
S_{ut} = Tensile strength

3 RESULTS

Coulomb-Mohr failure factors were calculated at each node of the finite element mesh in each time interval. For safety this factor should be less than 1. A factor equal to 1 or higher is an indication of possible material failure. The risk of material failure gets reduced as the value of this failure factor decreases towards 0. Risk gets increased when failure factor increases towards 1. The critical failure factors were 0.45 and 0.34 respectively for Rantambe and Moragahakanda dams during an earthquake with 0.1g peak ground acceleration. Figure 8 shows contour maps of Coulomb-Mohr failure factor at the time when the critical value of the factor occurs.

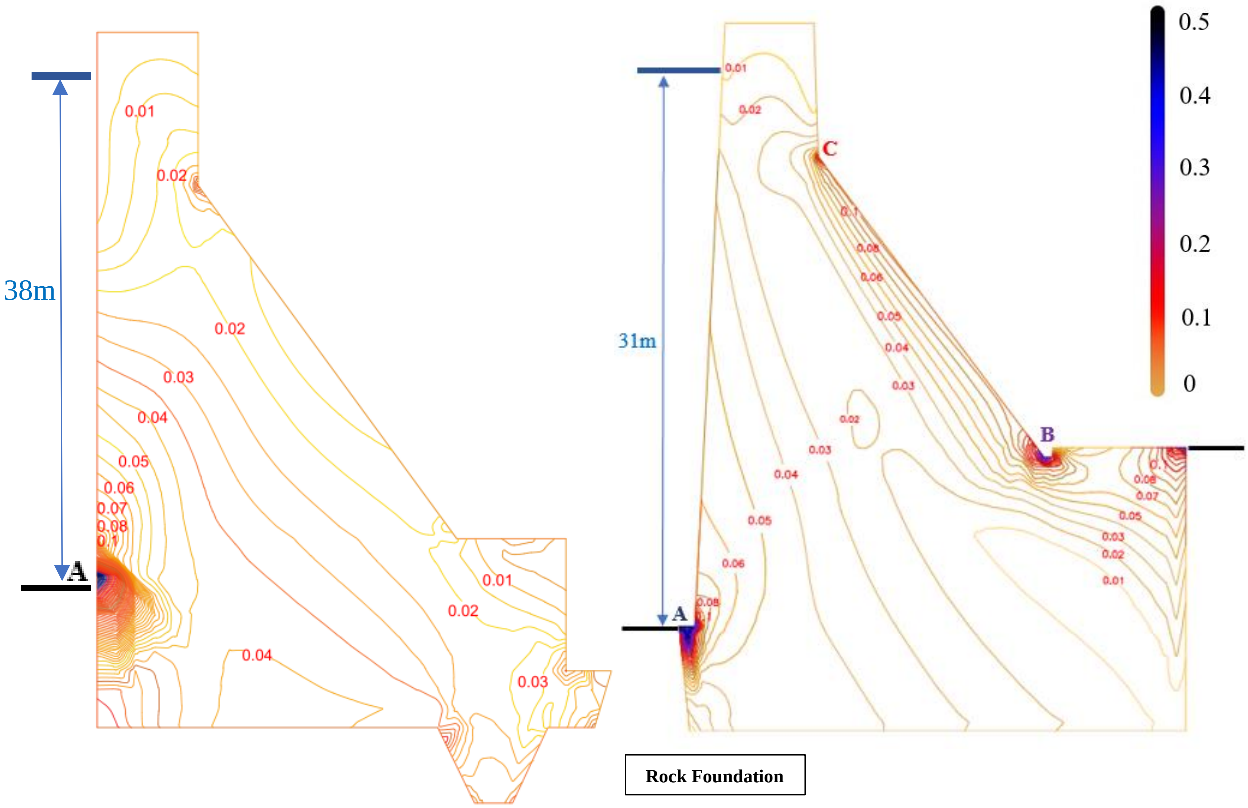


Figure 8. Coulomb-Mohr failure factor distribution on dam at the time interval which critical failure factor occurs at peak ground acceleration of 0.1g
(Left -Moragahakanda and Right -Rantambe)

For Rantambe dam, critical failure factor of 0.45 occurred in location A in Figure 8 (31 m below water level) and 2nd and 3rd largest values of 0.24 and 0.14 in locations B and C respectively. For Moragahakanda dam, the critical failure factor that occurred in location A in Figure 8 (38 m below water level) is 0.34.

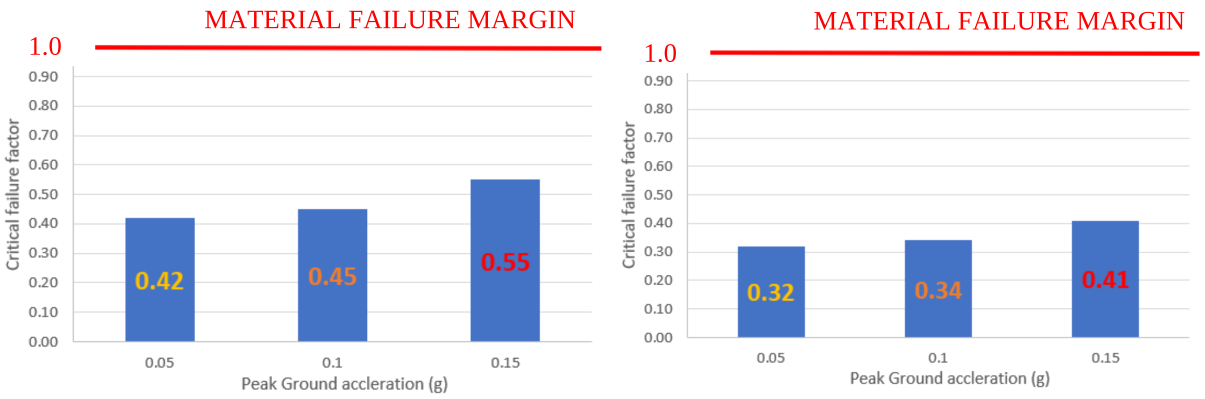


Figure 9– Critical Coulomb-Mohr failure factor variation with Peak Ground acceleration
(Rantambe-Left, Moragahakanda –Right)

The calculations were repeated for peak ground accelerations of 0.05g and 0.15g. The variation of the critical failure factor is shown in Figure 9. Even with peak ground acceleration of 0.15g the critical failure factor in Rantambe dam and Moragahakanda dam did not exceed the limiting value of 1. Therefore, material failure is unlikely in both dams for peak ground acceleration values up to 0.15g. In this connection it should be noted that the maximum peak ground acceleration recommended by Senevirathne et al. (2020) for critical structures in the relevant areas is 0.1g.

4 DISCUSSION

Rantambe dam is unlikely to experience material failures under earthquake loads having peak ground acceleration values up to 0.15g. Critical Mohr-Coulomb failure factor is 0.55 for Rantambe dam. (Figure 9). Moragahakanda dam also is unlikely to suffer any material failure up to a peak ground acceleration of 0.15g. Critical Mohr-Coulomb failure factor is 0.41 for Moragahakanda dam. These values are well within the allowable value 1.

In Rantambe dam the critical values were generated at sharp corners in the model where stress concentrations are likely to occur.

In Moragahakanda dam, critical failure factor occurs at the location A where different material layers meet. In such places also stress concentrations are likely to occur due to discontinuities in material properties.

Actual failure factor values might be slightly higher than the estimated values in both cases because some external forces were not considered in the analysis. Examples are tail water pressure, uplift pressure, and silt pressure. However the effects of these forces would be quite small.

When analyzing the stress distribution on the dam body, it is clear that critical stresses on the dam surface rapidly decrease when moves deeper into the structure of the dam. As a result, the middle of the dam has extremely low failure factors.

5 CONCLUSION

Sri Lanka is considered a non-seismic country. However, the possibility of an earthquake cannot be totally disregarded. Therefore, seismic analysis of dams is an important aspect of disaster preparedness. In the present work seismic analyses were performed for Rantambe and Moragahakanda dams under earthquake loads with peak ground acceleration values up to 0.15g. 2D finite element models were developed for both dams and time history analyses were carried out using SAP2000 software. Resulting stresses were examined using Coulomb-Mohr failure criterion.

The results indicate that both Rantambe and Moragahakanda dams are unlikely to have material failures even with a peak ground acceleration value of 0.15g. However, these results should be treated with caution. The analyses were performed using only one earthquake record. The results are preliminary at best. For a more definitive conclusions further comprehensive analyses need to be carried out under several different earthquake records and appropriate variations of time history analysis parameters.

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