Impact of seismic coefficient and slope angle on a gravity dam through numerical simulation

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A dam is a structure that aids the growth of a country in terms of infrastructure development. For such a magnificent structure design, its stability is vital. The Cheruthoni dam in Kerala, India (gravity dam) was selected for the present study. The reservoir-full condition, hydrostatic pressure, uplift pressure and earthquake pressure forces were chosen for failure analysis by considering seismic coefficient and downstream slope angle as critical parameters. The analysis was done regarding stress and displacement, and the results were interpreted using RS2 software. The results revealed that the downstream slope angle is more critical than the seismic coefficient.

Keywords: Gravity dam, numerical modelling, slope angle, stress and displacement.

FOR a highly populated and developing country like India, the quantum of industrial development is significant. For industrialization, the main sources are electricity and raw materials. A dam is a structure that stores water by forming a reservoir, and its major usage is in water supply, irrigation, power generation, and controlling floods. Dams also play an important role in the development of a country. Along with the benefits associated with dam construction, it is also associated with a few environmental costs like riparian habitat loss, water loss through evaporation, seepage and erosion. As dams play an important role, they should remain stable and functional under various conditions.

A gravity dam, one of the various types of dams, is considered for the present study. It is a structure made up of concrete or masonry constructed across a river to create a reservoir on its upstream. This dam has a unique feature, and it can resist the various forces acting on it by its self-weight, provided it is constructed on a strong foundation[1]. The design of a gravity dam is rather simple since it is a triangular-shaped cross-section in which the upstream face may be vertical or constructed as a slope, and the downstream is always constructed as a slope.

A dam is a massive structure and its construction, starts with a high initial cost. However, due to various advantages and increasing demand, dam constructions are done in collaboration with Government agencies. The instability in such massive structures can cause economic as well as environmental loss. Hence, the stability of a dam is vital. Among the various types of dams, gravity dam can be constructed with minimum requirements and serves various purposes with less maintenance. The forces acting on a dam are the prime reason for creating instability in various forms like overturning, sliding, compression or tension failure. Thus, its behaviour needs to be analysed in terms of displacement and stress, which is possible through numerical simulation techniques. In the present study, Cheruthoni dam, a gravity dam in the Idukki district of Kerala, India, is considered. The two-dimensional (2D) analysis of this dam has been carried out using the finite element method (FEM)-based Rocscience 2-dimensional (RS2) software.

Forces acting on the dam

The major forces which cause instability of a dam include hydrostatic pressure, uplift pressure, self-weight of a dam, earthquake pressure and hydrodynamic pressure[2–6].

Hydrostatic pressure

It is an external force acting on the gravity dam and is the major cause of instability[2]. It acts at the centre of gravity of the pressure distribution diagram, at $H/3$ height from the base[3] and water pressure is equal to the area of the triangle formed[2].

Uplift pressure

The upward pressure of water leaks through the body of a dam and into the pores and fissures of the foundation[1]. According to the United States Bureau of Reclamation (USBR) guidelines, the strength of uplift pressure at the toe and heel of a dam is equal to the static water pressure intensity. The drainage gallery placed in the body of a dam aids in reducing uplift pressure.

Self-weight of a dam

This is the major resisting force and can be calculated from the product of the cross-sectional area of the dam section and 1 m length unit weight of dam material[1]. In the 2D analysis of a dam, its weight is calculated by dividing its

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Table 1. Effect of vertical acceleration under various conditions[5]

Direction of vertical acceleration	Position of foundation of the dam	Effective weight	Stress magnitude	Condition
Upward	Lifted upward (+)	Increases	Increases	Good condition
Downward	Move downward (–)	Decreases	Decreases	Poor condition

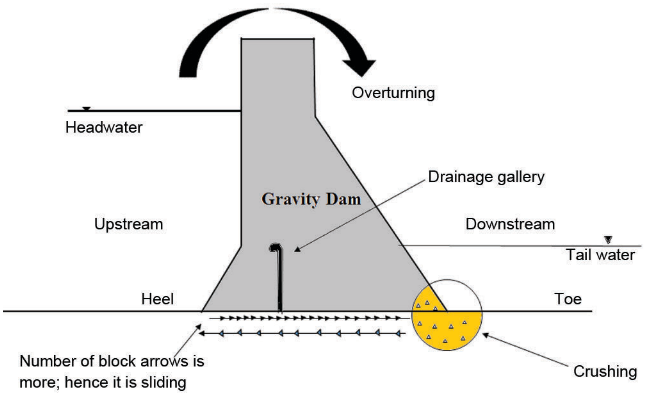

Figure 1. Types of failure of a gravity dam[7].

profile into rectangular and triangular cross-sections, and the result represents the total weight of the dam[2].

Earthquake pressure

Earthquake waves produce vibrations below the gravity dam in all possible directions[3]. The effect created by this is similar to the acceleration imparted to the foundation of a dam in the direction in which the wave travels at that moment. The earthquake waves move in all possible directions. However, for design purposes, they are resolved into horizontal and vertical components[2]. The effect of horizontal component can be determined by the inertia force in the body of a dam acts opposite to the direction of acceleration and is given by eq. (1).

$$F = W\alpha, \tag{1}$$

where F is the inertia force, W the weight of dam and α is the earthquake coefficient.

The vertical inertia force (α_w) opposes the direction of acceleration[4]. This changes the weight of the dam[5]. Table 1 shows its effect, which results in vertical acceleration.

Hydrodynamic pressure

According to Dawlatzai and Dominic[4], acceleration towards the reservoir induces a rise in water pressure that varies parabolically. The total pressure force acting at $4H/3\pi$ can be calculated from eq. (2).

$$P_e = 0.555\alpha\gamma_w H^2, \tag{2}$$

where P_e is the hydrodynamic pressure (kN/m^2), γ_w the unit weight of water (kN/m^3), α the earthquake coefficient and H is the height of dam (m).

In addition, Zanger has given a formula for computing the intensity of pressure derived by electrical analogy, assuming water as incompressible as Zanger's method[5]. The pressure variation is elliptic-cum-parabolic, and intensity at any depth (y) below mean water level (MWL) can be obtained using eq. (3)[6].

$$P_e = C_y\alpha\gamma_w y, \tag{3}$$

where C_y is the dimensionless pressure coefficient at y below the free surface.

In addition, there are few minor forces like wind, wave, silt, and ice pressure, which can be neglected as their effect is comparatively less.

Modes of failure

A dam must undergo a stability check for safety in the working phase as well as in the construction phase[1]. Figure 1 represents the types of failure in a gravity dam for stability check. As dam failure has economic consequences and affects human lives on a large scale, it must pass all the stability tests during its service life. The common modes of failure are discussed below in detail[6,7].

Overturning

The overturning of a dam occurs when the resultant of the forces acting on it cuts its base downstream, and the resulting moments at the toe turn clockwise. There will be no overturning if the resulting moments cut the base within the body of the dam. The required stability criterion to overcome overturning is given in eq. (4)[6]

$$\text{FOS}_{\text{overturning}} = \frac{\text{Sum of resisting moments at toe}}{\text{Sum of overturning moments at toe}} < 1.5. \tag{4}$$

Sliding

Sliding or shear failure occurs when the net horizontal force about any plane in the dam or its base exceeds the frictional resistance created at that level[6]. If the horizontal force causing sliding is greater than the resistance available at that level, the dam will fail in sliding.

Crushing or compression

A dam may fail by compression when the compressive stresses produced exceed the allowable stresses, and the dam material gets crushed. The vertical stress distribution at the base is given by eq. (5).

$$P_n = \frac{\Sigma V}{B}\left(1 \pm \frac{6e}{B}\right), \quad (5)$$

where P_n is the normal stress generated at the toe of dam, ΣV the net vertical force, B the base width of the dam and e is the eccentricity of the resultant force from the centre of the base. For safety of gravity dam against compression $P_n < F$. Where F is the forces generated in the body of the dam.

Development of tension in the dam body

Gravity dams are built in such a way that no stress develops in their body since concrete is brittle in tension and cannot withstand stress; as a result, the dam may fail. When tension cracks form at the heel, the width of the cracks loses contact with the base foundation, as a result, the effective width B of the dam base is lowered, resulting in an increase in P_{max} near the toe[6]. In order to have no tension anywhere in the dam, P_{min} must be zero. The eccentricity e of the resultant force can be calculated from eq. (6).

$$e = \frac{B}{6}, \quad (6)$$

where B is the base width of the dam.

Maximum eccentricity that can be permitted on either side of the centre is equal to $B/6$, which leads to the middle third rule, viz. 'The resultant must lie in the middle third'[7]. If this rule is not satisfied, the geometry needs to be revised.

Methods to analyse the stability of a gravity dam

Stability analysis of a gravity dam is generally carried out using two methods, viz. conventional method and numerical method-based software. Nowadays, due to advancement in this field of study and the reliability of the numerical method to analyse stability due to its accuracy of results, software-based stability analysis is more popular than the conventional methods which involve cumbersome calculations. The numerical methods avoid such calculations, reduce time and increase accuracy.

The US Bureau of Reclamation (USBR) published a design manual for concrete gravity dams. The manual outlines conventional methods to check for structural stability and assess potential modes of failure[8]. (i) Safe against overturning in the horizontal plane within the structure. (ii) Safe against sliding on any horizontal plane within the structure. (iii) Stress in concrete or foundation material shall not exceed the permissible limits.

Numerical simulation methods

Applying numerical simulation methods in dam stability analysis is taken from literature[9–13]. CADAM is the first numerical method-based software developed, which works on the gravity method using rigid body equilibrium and beam theory to perform stress analysis to compute crack width and factor of safety[9]. The stability analysis of a gravity dam is performed using finite difference strength reserve method with partial safety factor is carried out when complicated foundation with multiple slide planes are present, this study is performed on the dam which is located in China with the help of FLAC 3D software[10].

Moftakhar and Ghafouri[11] performed a comparative study of stability control and safety factors by various approximate methods of the US Army Corps of Engineers (USACE), US Bureau of Reclamation (USBR), and US Federal Energy Regulatory Commission (USFERC) used for a gravity dam. The results obtained from this methods were compared with the ANSYS software as well as with uplift pressure distribution regulation results.

The stability of a concrete gravity dam under different load conditions by varying the water level was analysed using the STAADPRO software[2]. This software finds applications in analysing the static and seismic stability of a gravity dam. It is based on the gravity (approach) method, which uses rigid frame equilibrium and beam approach for pressure analysis also to calculate crack length.

Dawlatzai and Dominic[4] stated that the stability analysis of Koyna dam was performed using the gravity method considering all the parameters and the overflow section of this Koyna dam was analysed using 2D finite element-based ANSYS APDL R.18.2 software. Pajand R. stated that this study deals with reviewing several methods used for dynamic analysis of gravity and Arch dam[12].

RS2 is a sophisticated, 2D finite element software used for various civil and mining engineering structures. It provides highly precise results by dividing the model developed into a number of triangles in the form of a mesh[13]. This software was developed and created by combining expertise with the most modern breakthroughs in underground analysis and computer technology. Hence, it is utilized to model the subsurface and surface workings for any study. In the present study, RS2 software has been used for numerical simulation.

Case study

The Cheruthoni dam lies in earthquake zone 2 (Figure 2)[14]. It is the same earthquake zone as the Koyna dam, in which earthquake waves caused harm to human life and property

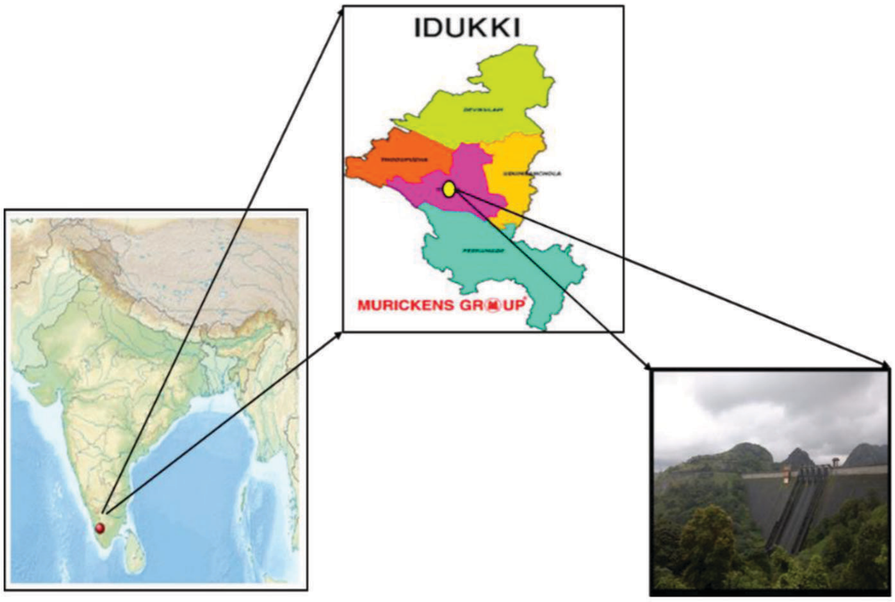

Figure 2. Location of the Cheruthoni Dam, Kerala, India[14].

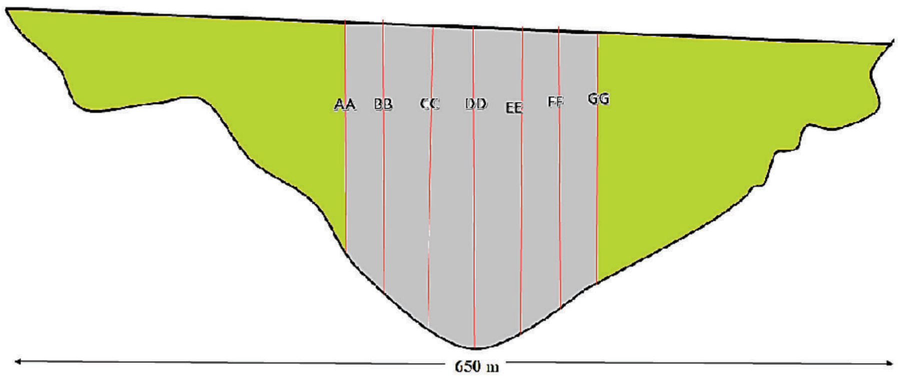

Figure 3. Selected sections along the length of the dam.

Table 2. Geometrical parameters of each section

Section	Height of section (m)	Width of section (m)	Remarks
AA	95.4	72	Nonoverflow
BB	108.6	79.94	Nonoverflow
CC	126	92.82	Nonoverflow
DD	132.6	94.90	Overflow
EE	136.5	95.49	Overflow
FF	114.9	84.62	Nonoverflow
GG	77.7	57.06	Nonoverflow

on a large scale in 1967. A study on the Koyna dam was carried out by Anas[15] using a dam-break analysis. The parameters required to check the stability of the Cheruthoni dam were obtained from the literature[16]. The dam height is about 138 m and 39 concrete blocks have been used along its length over 650.9 m. Among these, blocks 19 and 24 have deep sluices in them. Blocks 20–23 are overflow sections having an ogee spillway at the top to dispose of excess water, and the rest are non-overflow sections to hold water by forming a reservoir. In this study, the head available upstream (*U*/*s*) is 136 m and at downstream (*D*/*s*) is 21 m. The type of rock present in the foundation is coarsely crystalline charnokite[17].

Development of a model

The development of dam sections is based on the RS2 software. For analysis, seven sections were selected laterally (Figure 3). Table 2 shows the detailed geometrical parameters of all the sections. AA, BB, CC, FF and GG are the non-overflow sections with a top width of 7.32 m. DD and EE are the overflow sections in which water will flow over the crest of spillway. The passage of water over the spillway is 12 m, i.e. a gate of 12 m has been installed above the crest of spillway. Depending upon the head of water

Table 3. Designation for sections 4 and 5 based on height of flow over spillway

Details of section 4		Details of section 5	
Depth of water above the crest of spillway (m)	Designation assigned	Depth of water above the crest of spillway (m)	Designation assigned
No overflow	DD(A)	No overflow	EE(A)
3	DD(B)	3	EE(B)
6	DD(C)	6	EE(C)
9	DD(D)	9	EE(D)
12	DD(E)	12	EE(E)

Table 4. Grades of concrete and parameters used in modelling of the dam

Grade of concrete	Reduced level of the section from which specific grade concrete was used from the top (m)	Unit weight of concrete (kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Compressive strength (MPa)
M14	736.09	2580	20.6	0.19	14
M17	682.75	2580	21.9	0.182	17
M21	669.04	2580	23	0.17	21
M24	637.03	2580	24.2	0.17	24

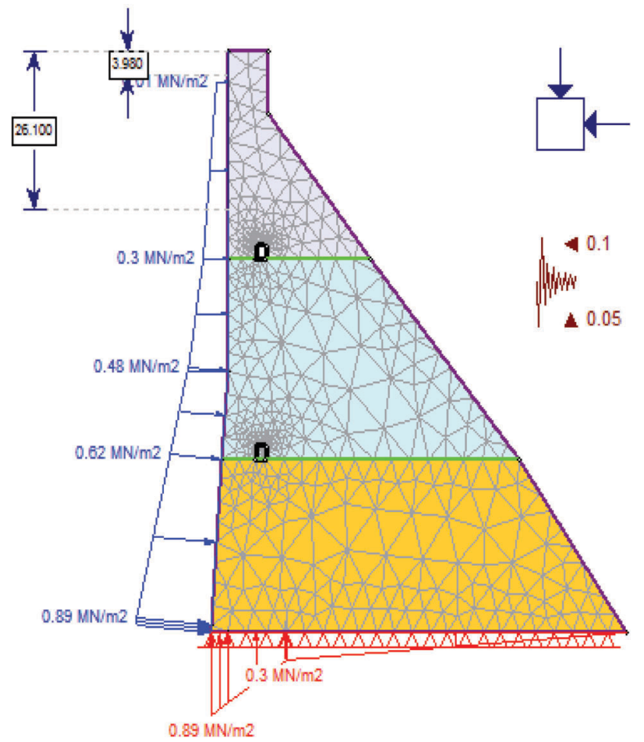

Figure 4. Geometry of section AA developed using RS2 software.

available, the gate is open for a specific head. In this study, overflow sections are divided into five sub-categories depending on the head of water allowed over the crest of spillway (Table 3).

Parameters used for modelling in RS2 software

In a gravity dam, weight is the main factor that influences its stability, which in turn depends on the grade of concrete. For the Cheruthoni dam, various grades of concrete have been used at different heights of the dam. Table 4 shows the parameters used for modelling. Figure 3 shows the sections selected for modelling.

Using the parameters mentioned in Table 4, models were developed in RS2 software to determine the stress and displacement of the dam section under different earthquake conditions to evaluate the stability of the dam with respect to earthquake and slope angle. Figure 4 shows the developed model for a non-overflow section AA. Similarly, models were developed for the remaining non-overflow sections BB, CC, FF and GG, and the overflow sections DD and EE.

Analysis of results in modelling

The models were developed to determine the stress and displacement of the dam section under different earthquake conditions for evaluating its stability with respect to both parameters (earthquake and slope angle). The results were interpreted in terms of displacement and stress. Graphs were plotted between different conditions of earthquake versus displacement and stress for all the sections.

Critical sections with respect to an earthquake

The stability of Cheruthoni dam with respect to seismic coefficient has been carried out. Table 5 mentions the zone factors or seismic coefficients according to the seismic zones of India. In this study, seismic coefficients or zone factors of 0.1, 0.2 and 0.3 were considered as they covered all the seismic zones as well as the future instability conditions due to earthquakes. After analysing with these values, only three sections were found to be critical. Table 6 gives

Table 5. Details of critical sections with respect to an earthquake using stress and displacement criteria

Zone number	Zone factor
I	–
II	0.10
II	0.16
IV	0.24
V	0.36

Table 6. Details of critical sections with respect to an earthquake using stress and displacement criteria

Critical section	α_h	Mean stress (MPa)	Displacement	Condition
DD(B)	0.3	1.34	10	Downstream upward (DU)
GG	0.3	1.19	10	Downstream downward (DD)
GG	0.3	1.10	10	Downstream upward (DU)

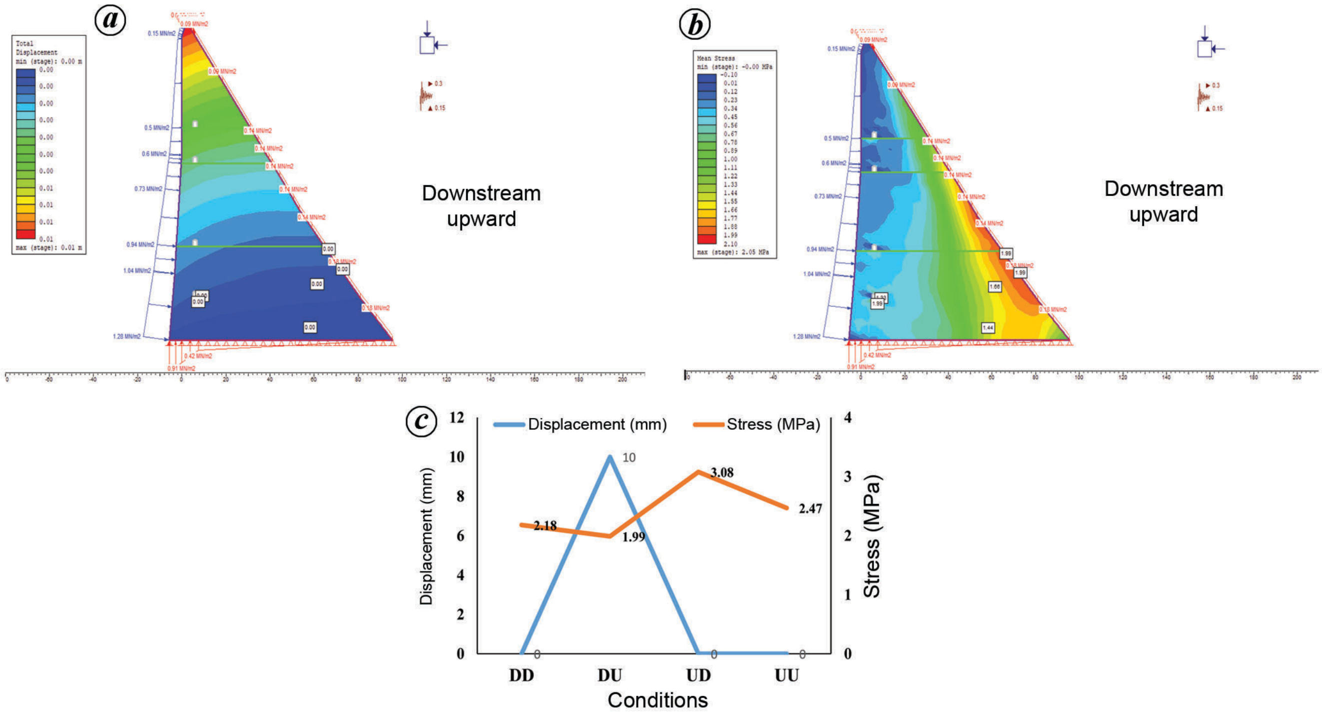

Figure 5. ***a***, Displacement in section DD(B) (α_h = 0.3). ***b***, Stress in section DD(B) (α_h = 0.3) (downstream upward). ***c***, Graphical representation of different conditions versus displacement and stress (α_h = 0.3) of section DD(B).

details of these sections are mentioned. The analysis was carried out for four different conditions, i.e. downstream downward (DD), upstream downward (UD), downstream upward (DU) and upstream upward (UU).

Figure 5 *a* and *b* shows the magnitude of displacement and stress obtained using the RS2 software for section DD(B). The graph plotted between different earthquake conditions for section DD(B) indicates that the dam is safe in sliding for the horizontal seismic coefficients 0.1 and 0.2 but for the horizontal seismic coefficient 0.3. In Figure 5 *c*, a displacement of 10 mm is observed due to pressure of water on the back of the dam, which eventually leads to its sliding. So, it has proved to be a critical condition and the reason for the instability of the dam section. All these sections are safe from crushing or compression failure, as the stress does not exceed permissible limits.

Figure 6 *a* and *b* shows the magnitude of displacement and stress respectively, obtained using the RS2 software for section GG for condition DD. While Figure 6 *c* and *d* respectively for condition DU. From this analysis, the dam

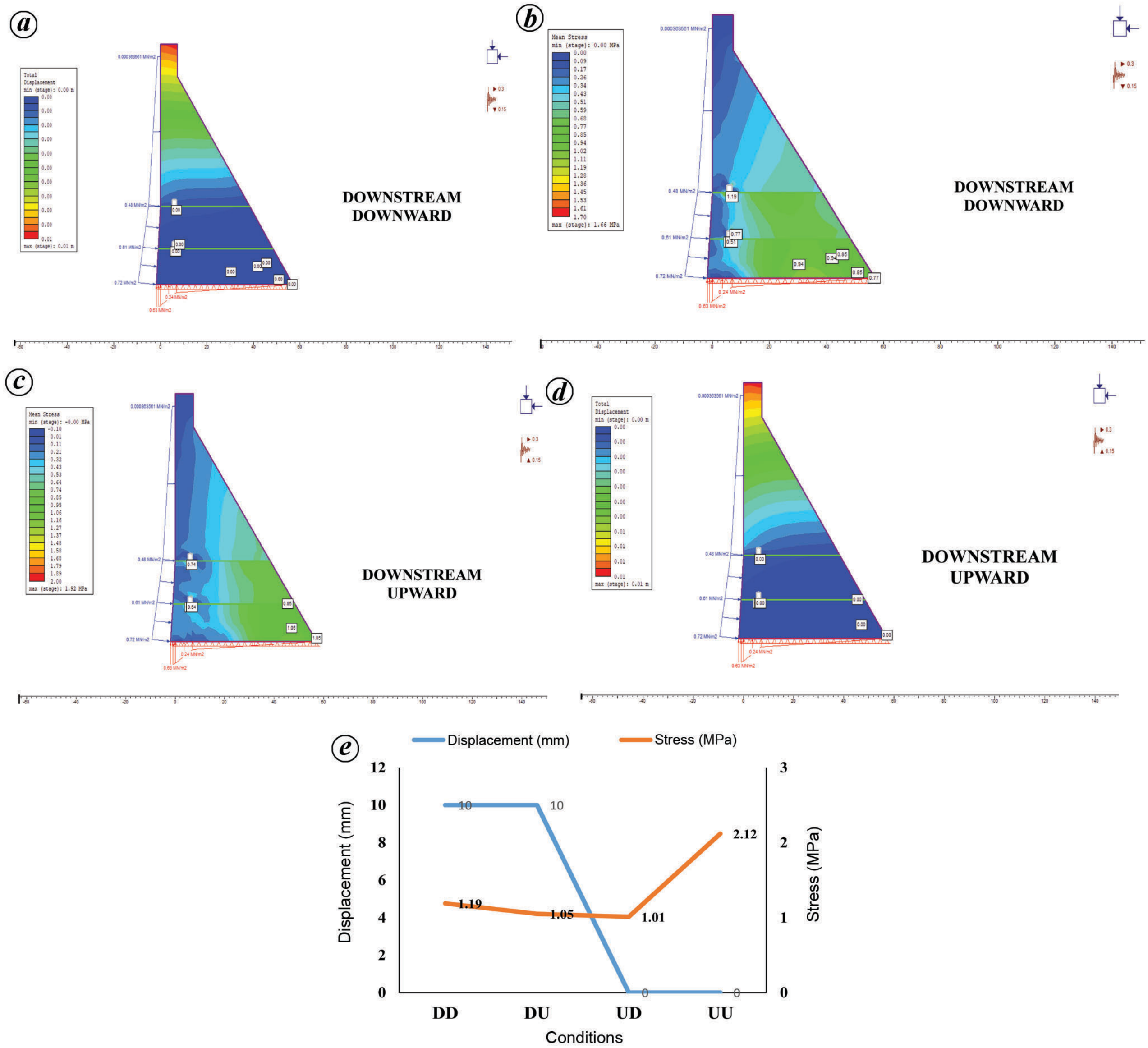

Figure 6. ***a***, Displacement in section GG ($\alpha_h = 0.3$) (downstream downward). ***b***, Stress in section GG ($\alpha_h = 0.3$) (downstream downward). ***c***, Stress in section GG ($\alpha_h = 0.3$) (downstream upward). ***d***, Displacement in section GG ($\alpha_h = 0.3$) (downstream upward). ***e***, Graphical representation of different conditions versus displacement and stress ($\alpha_h = 0.3$) of section GG.

Table 7. Critical overflow sections in terms of slope angle

Critical section	Condition	Slope angle	Height of flow (m)	Displacement (mm)	Stress (MPa)
	DU	0.6	3	10	3.19
DD	DU	0.6	6	10	2.68
	DU	0.6	9	10	2.70
	DU	0.6	12	10	2.71
	DD	0.6	3	10	2.35
	DD	0.6	6	10	2.32
	DD	0.6	9	10	2.31
EE	DD	0.6	12	10	2.30
	DU	0.6	3	10	2.80
	DU	0.6	6	10	2.86
	DU	0.6	9	10	2.50
	DU	0.6	12	10	2.18

is found to be safe in sliding for the horizontal seismic coefficients 0.1 and 0.2. However, for the horizontal seismic coefficient 0.3, a displacement of 10 mm is observed for conditions DU and DD (Figure 6 *e*). The stress value varies between 0.5 and 2 MPa, as observed in this section and under permissible limits for all grades of concrete.

Critical sections with respect to slope angle

The slope angle is considered a downstream slope of the dam section and is the main governing factor affecting a dam's stability. Originally, the downstream slope had a value of 1 in 0.74. In this study, the slope angle was taken as 1 in 0.7 and 1 in 0.6 for analysis. These values were

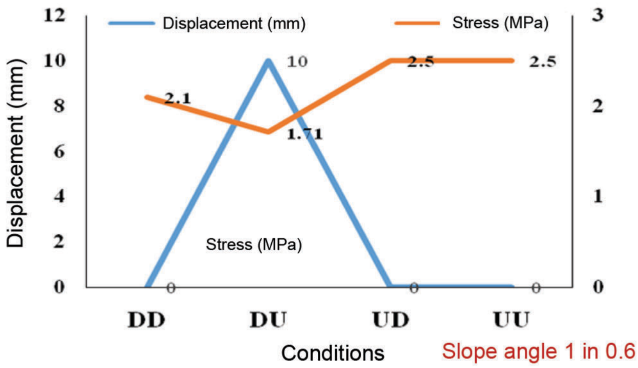

Figure 7. Graphical representation of different conditions versus displacement and stress of section AA.

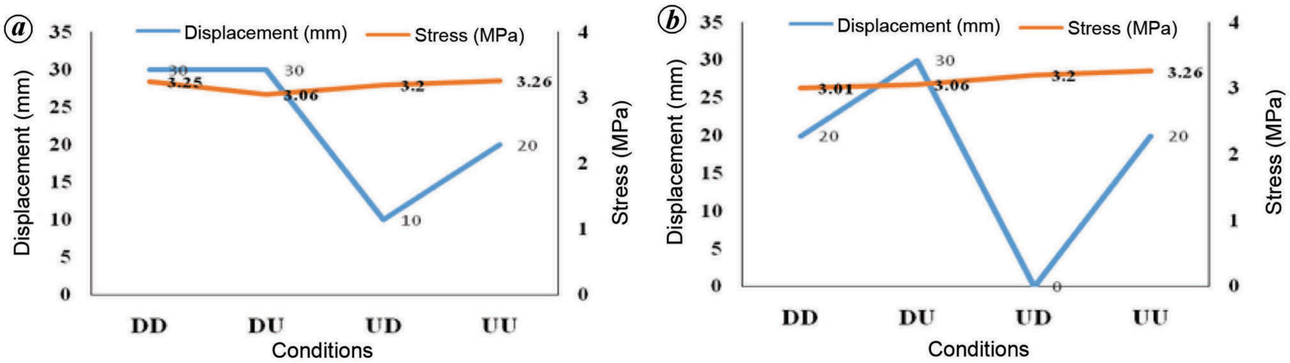

Figure 8. Graphical representation of different conditions versus displacement and stress of section BB. (***a***) Slope angle 1 in 0.6 and (***b***) slope angle 1 in 0.7.

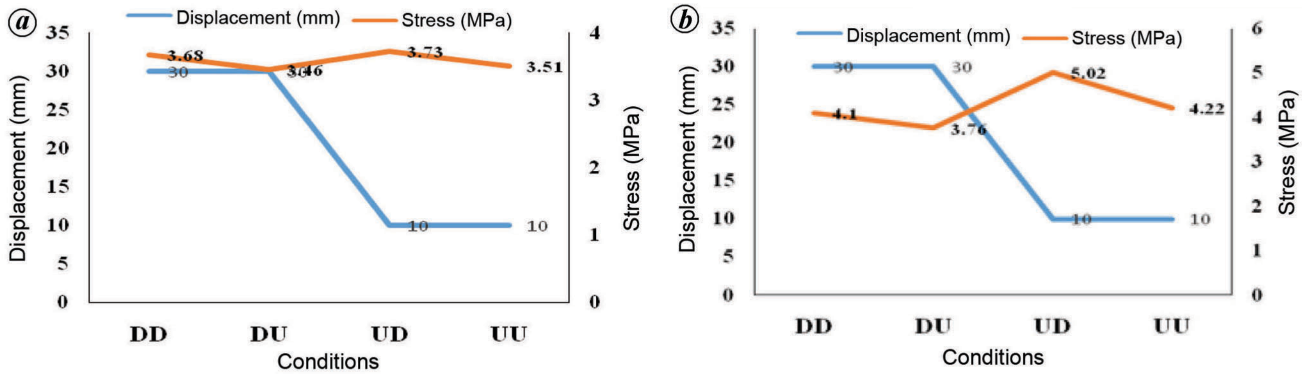

Figure 9. Graphical representation of different conditions versus displacement and stress of section CC. (***a***) Slope angle 1 in 0.6 and (***b***) slope angle 1 in 0.7.

selected based on the middle third rule, and hence, values of slope angle less than 1 in 0.6 were not considered for analysis. Likewise, values greater than 1 in 0.74 were also not considered for this study because, for these values, all the sections are safe. The critical sections identified from the analysis are discussed below. Table 7 shows the results obtained from the RS2 software for critical overflow sections with respect to slope angle different conditions, and the stress values in all the cases are found to be under permissible limits, which indicates that these sections are safe under the crushing criterion.

As observed from Table 7, the overflow sections DD and GG are found to be critical with slope angle 1 in 0.6 for earthquake conditions DD and DU. FF proves to be the most critical section, with a displacement of 10 mm for both (overflow and non-overflow sections) which leads to sliding.

Considering the non-overflow sections, analysis of section AA revealed that the downstream slope changes from 1 in 0.74 to 1 in 0.6, and the stability of the dam is reduced, which leads to sliding and displacement of 10 mm as observed for condition DU (Figure 7). In this case, tension failure will

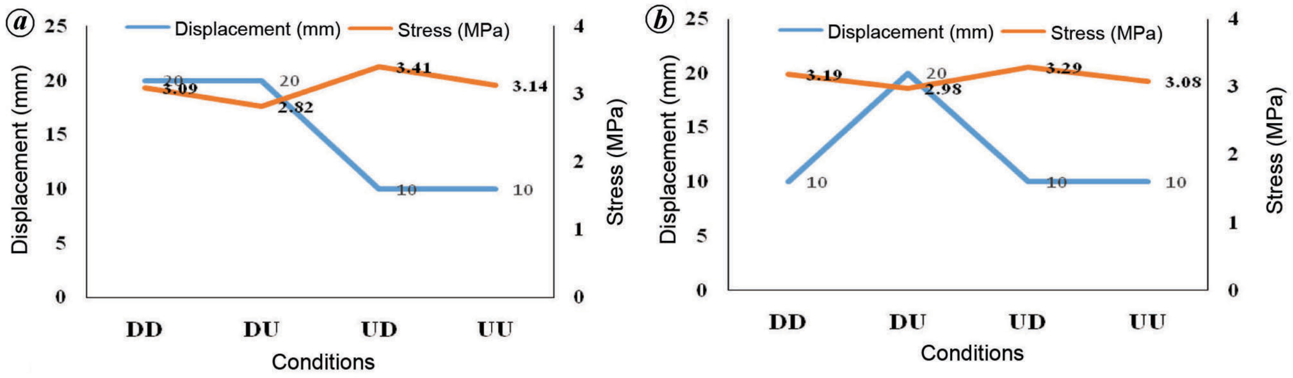

Figure 10. Graphical representation of different conditions versus displacement and stress of section FF. ***a***, Slope angle 1 in 0.6 and ***b***, slope angle 1 in 0.7.

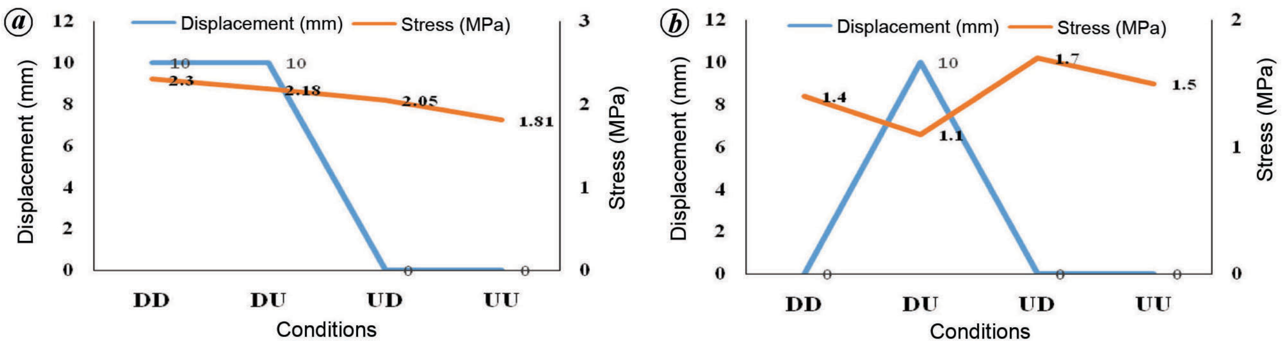

Figure 11. Graphical representation of different conditions versus displacement and stress of section GG. ***a***, Slope angle 1 in 0.6 and ***b***, slope angle 1 in 0.7.

occur and the resultant will not pass through the 1/3rd of the length of base of the section.

From the results of analysis of section BB, shown in Figure 8, displacement is found to occur for all earthquake conditions, i.e. 30, 30, 10 and 20 mm, for downstream slope angle 1 in 0.6. This is considered the most unstable section with larger displacement which leads to tension failure along with sliding. This leads to tension failure along with sliding failure. For slope angle 1 in 0.7, displacements of high magnitude as 20, 30 and 20 mm occur for conditions DD, DU and UU respectively, leading to an unstable condition.

From the results of analysis of section CC, represented in Figure 9, it can be observed that displacement takes place for all earthquake conditions, i.e. 30, 30, 10 and 10 mm, for both the slope angles, which leads to sliding of the structure.

From the results of analysis of section FF, shown in Figure 10, it can be observed that displacement takes place for all earthquake conditions, i.e. 20, 20, 10 and 10 mm for slope angle 1 in 0.6, and 10, 20, 10 and 10 mm for the slope angle 1 in 0.7, which shows unstable behaviour.

Figure 11 shows the results of analysis of section GG in which a displacement of 10 mm is observed for the earthquake conditions DD and DU for slope angle 1 in 0.6 and a displacement of 10 mm is observed for condition DU for slope angle of 1 in 0.7, which leads to sliding.

Discussion

Considering these results, no displacement is favourable in the sections since the displacement of a smaller magnitude (even 1 mm) tends to create a passage for the flow of water from upstream to downstream. This flow of water ultimately leads to the failure of the dam. Hence, zero displacement indicates a safe value for dam sections. Similarly, if stress is below the permissible strength of concrete (compressive strength of concrete is shown in Table 4), it is considered safe in crushing or compression failure of the dam for all the sections (overflow and non-overflow). From the results obtained for earthquake coefficients using the RS2 software, it can be observed that three critical conditions exist, i.e. one from section DD(B) and two from sections GG under conditions DU and DD. For seismic coefficient of 0.3, sections DD(A) and section GG prove to be critical with a displacement of 10 mm, which leads to sliding. However, for DU and DD conditions, the maximum stress of 2.05 and 1.92 MPa respectively, occurs in the section.

By changing the slope angle from the site condition, i.e. 1 in 0.74 to 1 in 0.7 and 1 in 0.6, the number of critical cases for slope angle 1 in 0.6 is found to be more when compared to slope angle 1 in 0.7. This proves that slope angle is the major parameter to be dealt with in terms of stability. Few sections having slope angle 1 in 0.7 and 1 in 0.6 have maximum displacement of 30 mm as the resultant of all the forces does not pass through the middle third of the base of the section to create tension in the dam body and the dam may fail. DD(A) proves to be the most critical among all overflow sections with a displacement of 10 mm and maximum stress of 3.19 MPa in terms of slope angle for condition DU. CC is the most critical section among all the non-overflow sections with a displacement of 30 mm and maximum stress of 4.10 MPa in terms of slope angle for condition DU. As the stresses obtained for all the sections with respect to both earthquake coefficient and slope angle are within permissible limits, these sections are found to be safe in resisting crushing stress.

Conclusion

We have studied the impact of earthquake coefficient and slope angle on the Cheruthoni dam using the RS2 software. From the results, stresses generated in all the cases are found to be within permissible limits, indicating that dam sections are safe against crushing. A few critical sections are found with displacement, which indicates sliding; this is more in the case of slope angle parameter. The present highlights the significance of earthquake coefficient and slope angle in the stability analysis of a gravity dam. Nevertheless, a dam should undergo all stability checks to prevent failure.

Conflict of interest: The authors declare that they have no competing interests.

1. Singh, R. B., Dam section optimization using Monto Carlo simulation and genetic algorithm, Ph.D. thesis, Water Resource Engineering, VNIT, 2015.
2. Nallanathel, M., Ramesh, B. and Raju, P. K., Stability analysis of concrete gravity dam using STAAD PRO. *Int. J. Pure Appl. Math.*, 2018, **119**(17), 297–310.
3. Ali, H., Alam, R., Haque, N. and Alam, M. J., Comparison of design and analysis of concrete gravity dam. *Nat. Resour*., 2012, **3**(6), 18–28.
4. Dawlatzai, K. and Dominic, M., Structural stability and 2D finite element analysis of concrete gravity dam. *Int. J. Eng. Sci. Inven.*, 2018, **7**(1), 9–20.
5. Anon., https://theconstructor.org/water-resources/forces-acting-dam-structure/5251/ (accessed on 9 May 2022).
6. Garg, S. K., *Irrigation Engineering and Hydraulic Structure*, Khanna Publisher, Delhi, 2002.
7. Anon., https://viderime.com/civil-engineering/irrigation-amp-hydrology/modes-of-failure-of-gravity-dam/ (accessed on 5 May 2022).
8. Colorado, D., *Design Manual for Concrete Gravity Dams*, US Department of the Interior, Bureau of Reclamation, USA, 1976.
9. Leclerc, M., Leger, P. and Tinawi, R., Computer aided stability analysis of gravity dams – CADAM. *J. Adv. Eng. Softw*., 2002, **34**, 403–420.
10. Xuhua, R., Jiaqing, S., Nenghu, B. and Hongyun, R., Stability analysis of concrete gravity dam on complicated foundation with multiple slide planes. *J. Water Sci. Eng.*, 2008, **1**(3), 65–72.
11. Moftakha, M. and Ghafouri, H. R., Comparison of stability criteria for concrete dams in different approximate methods based on finite element analysis. In 12th East Asia-Pacific Conference on Structural Engineering and Construction, Shahid Chamran University of Ahvaz, Iran, 2011.
12. Sani, A. A., Kazemiyan, M. S. and Pajand, M. R., A literature review on dynamic analysis of concrete gravity and arch dams. *Arch. Comput. Meth. Eng.*, 2021, **28**, 4357–4372.
13. Anon., https://www.rocscience.com/help/rs2/documentation (accessed on 7 May 2022).
14. Sudeer, K. P., Murty, B. S., Narasimhan, B., Thomas, J., Bindhu, V. M., Vema, V. and Kurian, C., Role of dams on the floods of August 2018 in Periyar River Basin, Kerala. *Curr. Sci.*, 2019, **116**(5), 780–794; https://doi:10.18520/cs/v116/i5/780-794.
15. Anas, S. K. and Varughese, R. A., Cheruthoni dam break analysis. *Int. J. Eng. Res. Technol*., 2021, **10**(6), 841–844.
16. Kishen, C. J. M., Recent developments in safety assessment of concrete gravity dams. *Curr. Sci.*, 2005, **89**(4), 652–656.
17. Anon., https://www.wikiwand.com/en/Cheruthoni_Dam#/Gallery (accessed on 8 May 2022).

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