Challenge Journal of Concrete Research Letters

Research Article

The effect of the gravity on the earthquake performance of roller compacted concrete dams

Fethi Şermet [a,*], Murat Emre Kartal [b], Muhammet Ensar Yiğit [c], Emin Hökelekli [d]

[a] *Department of Civil Engineering, Iğdır University, 76000 Iğdır, Türkiye*
[b] *Department of Civil Engineering, İzmir Demokrasi University, 35100 İzmir, Türkiye*
[c] *Department of Civil Engineering, Manisa Celal Bayar University, 45100 Manisa, Türkiye*
[d] *Department of Civil Engineering, Bartın University, 74000 Bartın, Türkiye*

ABSTRACT

Roller compacted concrete (RCC) is a dry concrete mixture often utilized in the construction of large dams. The interlayer of the RCC dam, which is the weakest plane of the structure, can easily fail under hydraulic shear load, geological impact, earthquake force and environmental impact. In this study linear and performance analyzes were carried out for eight different scenarios for foundation effect, gravity effect and empty and full reservoir situations. In analyses, the earthquake response and performance of the Akçakoca RCC Dam, taking into account the interaction between the dam and the water. The reservoir water behavior is simulated using the Eulerian-Lagrangian coupled (CEL) approach with finite elements modeling. Linear analyses reveal that hydrodynamic pressure leads to increased displacements and principal stresses. The earthquake performance evaluation of the Akçakoca RCC dam indicates that critical concrete damages are expected based on linear time-history analyses conducted for both empty and full reservoir scenarios. Besides, according to this study, gravity effect clearly increases the earthquake performance of the dam.

ARTICLE INFO

Article history:
Received 23 November 2023
Revised 10 January 2024
Accepted 3 February 2024

Keywords:
RCC dams
Gravity effect
Hydromechanics
Structure dynamics
Performance analysis

1. Introduction

In recent years, the roller compacted concrete (RCC) dam has become increasingly popular as a modern dam construction method. RCC dams possess comparable structural strength to traditional concrete dams, and their construction process, resembling the technique used for roller compaction soil-rock dams, enhances operational efficiency in the field.

The increasing need for renewable energy has led to the construction of numerous high concrete dams, especially in seismically active regions. For example, there are many dams higher than 150 m in Türkiye. These dams are designed to withstand high foundation acceleration values, such as 0.50 g. Ensuring the seismic safety of these concrete dams is of paramount importance in the field of engineering. The seismic events possess the capability to interfere with the effective operation of these essential infrastructures, causing disastrous breakdowns that may lead to substantial human and property losses. Consequently, ensuring the seismic resilience of these dams has emerged as a vital focus for engineers and researchers.

Various theoretical methods have been suggested to forecast dam deformations and assess the current operational condition of dams (He et al. 2018; Dou et al. 2019; Yang et al. 2019; Zhang et al. 2019). However, in real-world situations, the integration of roller compacted concrete (RCC) with conventional concrete (CC) becomes inevitable. In projects characterized by challenging geological conditions and demanding construction timelines, a blend of both roller compacted concrete (RCC) and conventional concrete (CC) may be employed in the design and construction phases of dams. RCC con-

* *Corresponding author.* Tel.: +90-476-223-0040 ; E-mail address: fethi.sermet@igdir.edu.tr (F. Şermet)
ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2024.01.003

sists of the same components as conventional concrete: well-graded aggregates, cementitious materials, and water (Calis and Yıldızel 2019). The utilization of RCC in dam construction enables elevated productivity levels (Cervera et al. 2000), this approach can help in reducing construction time, compensating for delays in foundation treatment. It effectively relieves the pressure on the construction schedule, particularly for specific dam shapes. However, the distinct material properties and deformation characteristics of conventional concrete and roller compacted concrete raise concerns about structural safety. Specifically, notable deformation gradients are frequently observed at the interfaces where there are substantial volumes of diverse concrete materials (Luo et al. 2016).

The initiation, propagation, and coalescence of cracks within concrete structures are pivotal factors contributing to seismic damage and failure (Luo et al. 2016). Earthquake analyses on 2D finite fluid models in both linear and nonlinear time domains were conducted by Kartal et al. (2017), suggesting that the seismic behavior of the dam is impacted by the reservoir's length. Alembagheri (2020) introduced an approach to evaluate damage extent using linear seismic analysis results, with a specific focus on potential damage due to tension cracking in concrete. The methodology was illustrated and potential nonlinear responses and damage mechanisms were explored through the presentation of three examples involving concrete gravity dams. Wang et al. (2015) employed a two-dimensional fluid finite element approach incorporating the Lagrangian method for simulating the reservoir water. Considering the influence of dam reservoir-foundation interaction, they conducted a numerical investigation to predict potential failure modes of concrete gravity dams. Hariri-Ardebili et al. (2016) performed parametric finite element analyses on a standard concrete gravity dam. They modelled the unified dam-foundation-reservoir system using a Lagrangian-Eulerian approach. Their results suggested that primary potential failure modes of gravity dams include cracking along the length, cracking at the base, sliding, and overturning. Contrastingly, Huang (2018) introduced a comprehensive numerical framework for the analysis of seismic ruptures, which incorporates interactions among dam, reservoir, sediment, and foundation. This framework integrates a nonlinear extended finite element formulation, addressing material, geometric, and contact nonlinearities. Furthermore, it incorporates an adaptive time-stepping extended multiple transmission boundary. Applying this methodology, Sharma et al. (2020) explored the seismic cracking behavior of a representative concrete gravity dam system. They introduced a space-time finite element method for the dynamic rupture analysis of a dam-reservoir system supported on a completely rigid foundation. Similarly, Bayraktar et al. (2009) conducted earthquake performance analysis on the Torul Concrete Lined Rock Fill (CFR) Dam, utilizing two-dimensional finite element models and considering both dam-soil and dam-soil-reservoir interactions. In the analysis, a Lagrangian approach was utilized for fluid elements, and interface elements were incorporated to mimic the sliding behavior between the concrete surface slab and the rock fill material. These elements played a crucial role in accurately capturing the interactions and responses within the dam structure under seismic conditions. Liu et al. (2023) examined the risks of dam cracking during the construction phase, taking into account the spatial variability of thermodynamic parameters. Li et al. (2021) investigated the heightened risk of cracking in the dam body due to seismic damage in gravity dams, considering the spatial variability of tensile strength. This factor should be considered in seismic design. Additionally, there has been significant attention on time-varying reliability, as evidenced by previous studies (Wang et al. 2023; Liu et al. 2022; Li et al. 2022; Yin et al. 2023).

In this study, the impact of both gravity and earthquake forces on dam performance was investigated. The analysis encompassed eight different conditions, accounting for the dam body with and without foundation, considering gravity, and examining both full and empty dam conditions. Through these analyses, the performed solutions successfully determined the influence of foundation and gravity on the dam's performance.

2. Formulation of Eularian-Lagrangian Coupled Approach for Dam-Reservoir-Foundation Interaction

The Eulerian-Lagrangian Combined Approach is a useful method for investigating complex interactions within structures by considering both a broader spatial context and the behavior of individual elements. This comprehensive analysis aids in making informed decisions related to the safety, integrity, and risk assessment of structures. In the context of fluid dynamics and continuum mechanics, the Eulerian and Lagrangian definitions are two fundamental approaches used to analyze the movement and behavior of materials (Skrzat 2012).

The Eulerian-Lagrangian Coupled Approach is a robust method for studying complex interactions within dams, considering both overall spatial context and individual element behavior. This approach enables detailed analysis, aiding decisions on dam safety, structural integrity, and risk assessment. In fluid dynamics and continuum mechanics, Eulerian and Lagrangian descriptions are fundamental. Eulerian focuses on fixed spatial points, tracking property changes (e.g., velocity, pressure) over time. Lagrangian tracks individual particle motion, formulating equations based on specific particle properties, like position and velocity, at any given time.

The correlation between material and spatial time derivatives can be formulated as follows:

$$\frac{D\Phi}{Dt} = \frac{\partial\Phi}{\partial t} + v.(\nabla.\Phi) \tag{1}$$

In the context provided:

- In this expression, Φ denotes the arbitrary solution variable.
- The symbol v represents the material velocity.
- $D\Phi/Dt$ corresponds to the material time derivative.
- $\partial\Phi/\partial t$ signifies the spatial time derivative.

The equations conserving mass, momentum, and energy, initially developed within the Lagrangian framework, are transformed into Eulerian conservation equations that involve spatial derivatives. The specific process and methodology for this conversion are detailed in the reference provided by Benson and Okazawa (2004).

$$\frac{\partial \rho}{\partial t} + v.(\nabla.\rho) + \rho\nabla.v = 0 \quad (2)$$

$$\frac{\partial v}{\partial t} + v.(\nabla.v) = \frac{1}{\rho}(\nabla.\sigma) + b \quad (3)$$

$$\frac{\partial e}{\partial t} + v.(\nabla e) = \sigma{:}D \quad (4)$$

where ρ represents density, σ denotes the Cauchy stress, b is the vector of body forces, e stands for strain energy, and D represents velocity strain.

The equations in the Eulerian framework Eqs. (2) and (4) can be restructured into conservative formats as described in reference by Benson (1997).

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho v) = 0 \quad (5)$$

$$\frac{\partial \rho v}{\partial t} + \nabla.(\rho v \otimes v) = \nabla.\sigma + \rho b \quad (6)$$

$$\frac{\partial e}{\partial t} + \nabla.(ev) = \sigma{:}D \quad (7)$$

$$\frac{\partial \phi}{\partial t} = S \quad (8)$$

$$\frac{\partial \phi}{\partial t} + \nabla.\varphi = 0 \quad (9)$$

The Eulerian governing Eqs. (5) and (7) have a general form:

$$\frac{\partial \phi}{\partial t} + \nabla.\varphi = S \quad (10)$$

where ϕ represents the flux function, and S represents the source term. Eq. (10) is divided into two equations and solved sequentially using operator splitting, as described in reference.

Eq. (8) encompasses the source term that signifies the Lagrangian step, whereas Eq. (9) incorporates the convective term, representing the Eulerian step.

The deformed mesh, derived from the Lagrangian step, is mapped onto the stationary Eulerian mesh to solve Eq. (9). Subsequently, the volume of material displaced between neighboring elements is calculated. Parameters of the Lagrangian solution, such as mass, stress, and energy, undergo adjustments throughout the process to accommodate the movement of material between adjacent regions. The Lagrangian step utilizes the virtual work principle, as elucidated in reference to Bathe (1996), to facilitate these modifications.

$$\int_v \rho a.\delta u dv + \int_v \sigma{:}\delta\varepsilon dV = \int_S t.\delta u dS + \int_v \rho b.\delta u dV \quad (11)$$

The updated Lagrangian formulation is appropriate for the Lagrangian step because it corresponds to the present configuration in the Eulerian approach, which aligns with the reference configuration at time t. Predicting the body's configuration at $t+\Delta t$, as specified in Eq. (11), is fundamentally difficult. This prediction incorporates unknown elements such as integration volume and density, both of which are affected by the body's deformations.

3. Case Study: Akçakoca RCC Dam

3.1. Akçakoca Dam

The Akcakoca Dam, located approximately 17 km north of Düzce, was constructed in 2016 by the State Hydraulic Works of Turkey (Fig. 1). It was specifically designed and built as a roller-compacted concrete dam near the Akçakoca mouth. The resulting reservoir, formed by the dam, primarily serves irrigation purposes. The dam crest has a length of 150 meters and a width of 8 meters. It reaches a maximum height of 66 meters, with a base width of 62 meters. The water level in the reservoir reaches its peak at 62 meters.

Fig. 1. Akçakoca Dam (DSİ 2023).

The effect of gravity is often neglected when determining earthquake performance. Therefore, it is important to determine to what extent gravity will affect the dam performance whether it is included in the calculations or not. In the context of this study, various models were developed, including gravity and non-gravity models, as well as models with and without a foundation rock. These models were further categorized into empty and full dam configurations, resulting in a total of 8 distinct models for the analysis, as outlined in Table 1.

Table 1. Dam analysis models.

Cases	Water conditions	Gravity	Model
Case 1	Empty	Without	Dam Body
Case 2	Full		
Case 3	Empty	With	
Case 4	Full		
Case 5	Empty	Without	Dam-Foundation
Case 6	Full		
Case 7	Empty	With	
Case 8	Full		

3.2. Material properties of Akçakoca Dam

Akçakoca Dam's two-dimensional finite element model has a single-layered gneiss rock foundation. Table 2 shows the material parameters of the Akçakoca roller compacted concrete dam body and its foundation. As a concrete property, a mixture containing 60 kg/m^3 cement, 30 kg/m^3 fly ash and 125 lt/m^3 water was used as RCC mixture.

3.3. Finite element modeling of Akçakoca Dam

In this research, a 2D finite element model (FEM) is developed for the critical section of the Akçakoca Roller Compacted Concrete (RCC) dam using ABAQUS software. The model defines the dam's height as 'H,' and the foundation rock extends 'H' units in both the downstream river and gravity directions. Additionally, the foundation rock and reservoir water model extend '3H' units upstream. The fluid and solid element matrices are computed using the Gauss numerical integration technique, as per the methodology outlined by Wilson and Khalvati (1983). Specifically, the dam body (C3D8) is subdivided into elements with 2×2 integration points, the foundation rock (C3D8) is also divided into elements with 2×2 integration points, and the fluid element (EC3D8) incorporates 2×2 integration points.

Table 2. Material properties of Akçakoca roller compacted concrete dam (Sunbul et al. 2018; Kartal and Karabulut 2018).

	Modulus of elasticity (GPa)	Poisson's ratio	Mass density (kg/m^3)
Concrete (Dam Body)	28	0.2	2500
Gneiss	18	0.15	2800
Water	2.2	-	1000

We analyzed the maximum tensile and compressive stresses with respect to the dam height. Following that, we illustrated the maximum principal tensile and compressive stresses experienced during an earthquake on the upstream side of the dam body. This study involved an investigation of four different scenarios to identify the most critical conditions of the dam, as detailed below (Figs. 2-5).

First condition involves empty reservoir and galleries are excluded from dam body. This model has totally 1540 nodal points and 714 elements. Second condition involves full reservoir dam body. Contact elements were defined for the interaction surface. This model has totally 8990 nodal points and 4270 elements. Third condition involves empty reservoir and galleries are excluded from dam body. This model has totally 6092 nodal points and 2844 elements. Fourth condition involves full reservoir and galleries are excluded from dam body. Contact elements were defined for the interaction surface. This model has totally 13542 nodal points and 6427 elements.

3.4. 1999 Düzce Earthquake

The Düzce Earthquake occurred on 12 November 1999 at 18.57 local time (16.57 UTC) with a moment magnitude of 7.2. This seismic event resulted in significant damage, causing 845 fatalities and 4948 injuries in Düzce, Türkiye. The epicenter was located at coordinates 40.768° latitude and 31.148° longitude, with a moment magnitude of 6.2 (Mb), surface wave magnitude of 7.4 (Ms), seismic moment (Mo) of 4.5×10^{19} Nm, and moment magnitude of 7.1 (Mw) (Erdik 2000). For this study, the North-South (N-S) and vertical components of the 1999 Düzce accelerogram were utilized, as depicted in Figs. 6-7.

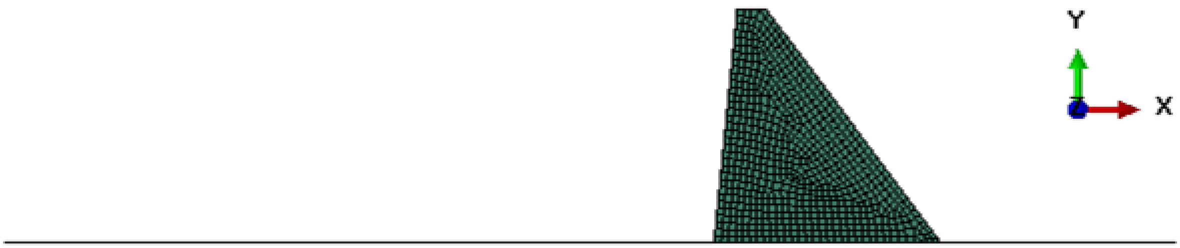

Fig. 2. Creating a finite element model for a dam in the absence of water in the reservoir.

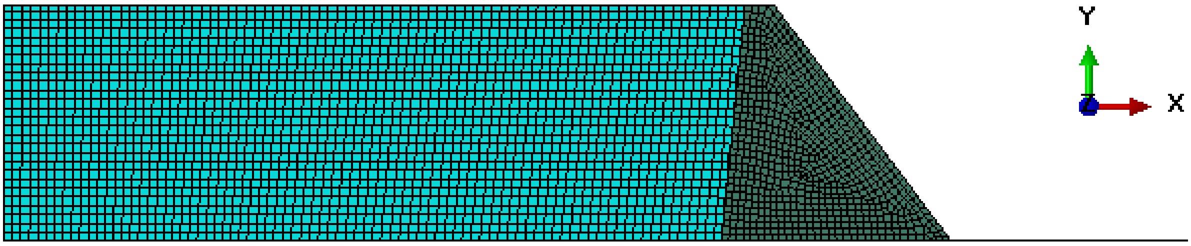

Fig. 3. Creating a finite element model for a dam with a full reservoir.

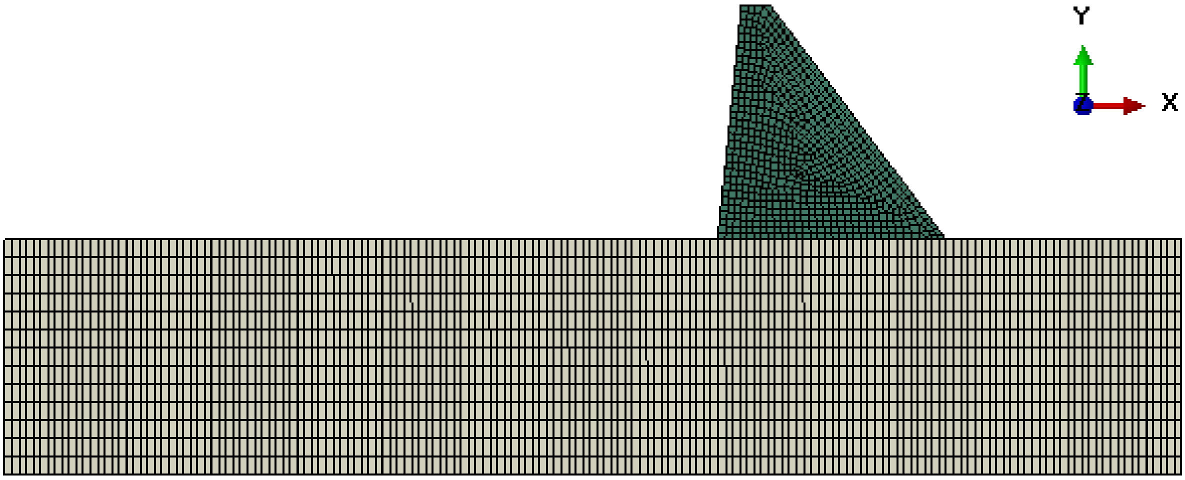

Fig. 4. Finite element model incorporating foundation rock for an empty reservoir.

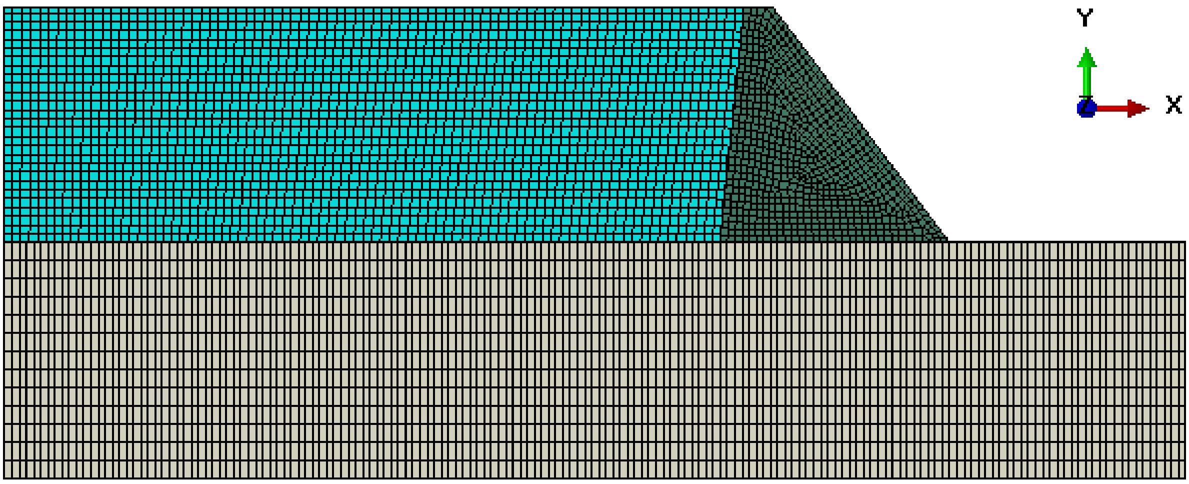

Fig. 5. Finite element model with foundation rock for a full reservoir.

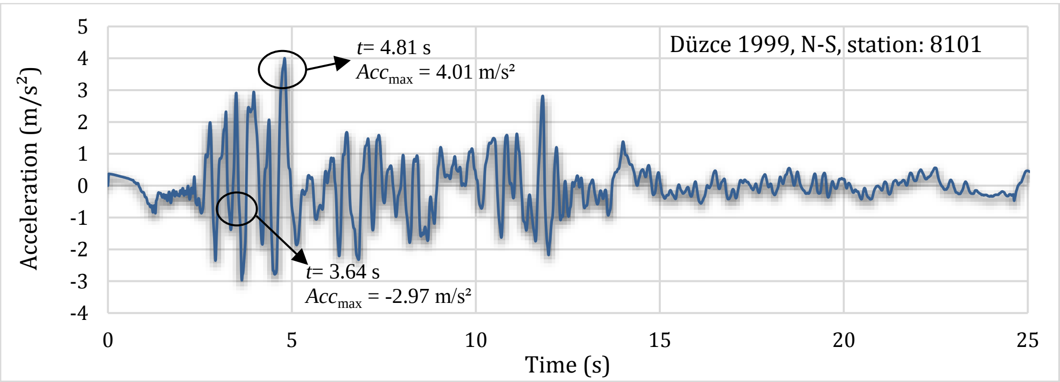

Fig. 6. 1999 Düzce Earthquake accelerogram for North-South direction (AFAD 2023).

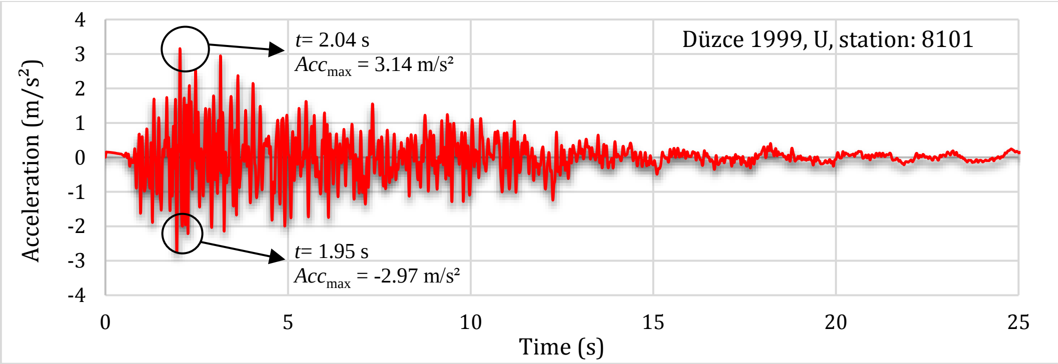

Fig. 7. 1999 Düzce Earthquake for vertical direction (AFAD 2023).

3.5. Optimum mesh density

In the upcoming numerical studies, it is crucial to create a finite element mesh that produces accurate results. To determine the optimal mesh, it is necessary to analyze various models with different numbers of finite element divisions and compare their outcomes. The finite element mesh plays a significant role, especially in areas where stress values suddenly increase.

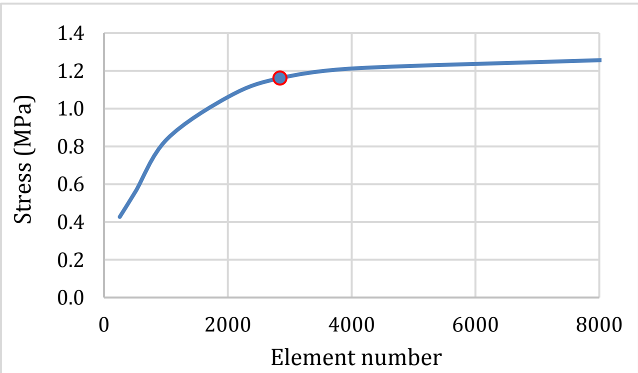

Fig. 8. Evaluation for optimum finite element mesh around upstream face thalweg.

Analyses were conducted using different discretized finite element meshes to observe stress increments resulting from sudden section loss around the gallery. The investigation focused on the dam body, where the number of optimum finite elements was determined based on the results obtained from numerical analyses. The outlined research methodology is depicted in Fig. 8.

4. Dynamic Analysis

Along the height of the dam's upstream face, the principal tensile stresses within the concrete are depicted. Figs. 9 and 10 show that the highest primary stresses drop when the reservoir is empty. Furthermore, when subjected to gravity acceleration, all models exhibit a decrease in maximum tensile stresses. When gravity acceleration is ignored, maximum tensile stresses rise in the full reservoir scenario compared to the empty situation.

5. Performance Analysis

The research investigates the seismic performance of the Akçakoca Roller Compacted Concrete (RCC) Dam, focusing on the impact of gravitational acceleration on its seismic behavior. The study considers both empty and full reservoir conditions, taking into account or neglecting the effects of gravity. Time-history analyses are conducted using the north-south and vertical components of the 1999 Düzce earthquake, as depicted in Figs. 6-7.

The evaluation of demand-capacity ratios, ranging from 1 to 2, is carried out for the primary tensile stresses experienced by the concrete. Figs. 11-14 depict the cycles of major tensile stresses derived from linear time-history analysis under various conditions. In the case of a full reservoir, the major tensile stresses consistently exceed the tensile strength of the concrete, as shown in Fig. 12a, even when the demand-capacity ratio (D/C) is equal to 2. Moreover, the tensile strength of the concrete is recurrently surpassed in the scenario of an empty reservoir. The presence of reservoir water, as indicated in Fig. 14, intensifies the primary tensile stresses.

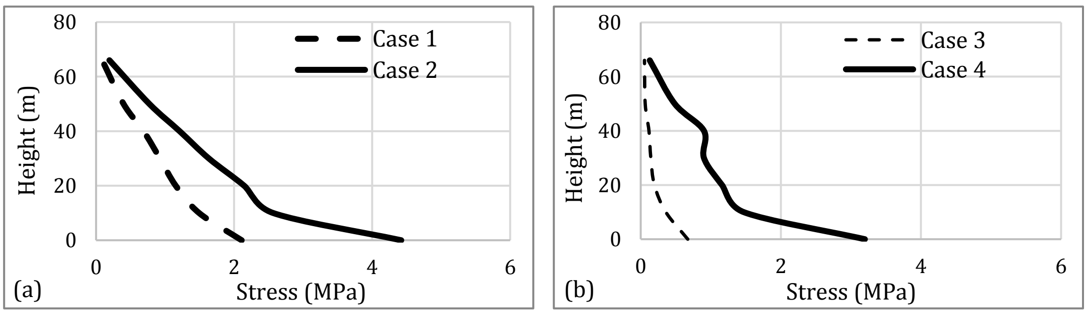

Fig. 9. Maximum principal tensile stress change by height for dam body: (a) Without gravity; (b) With gravity.

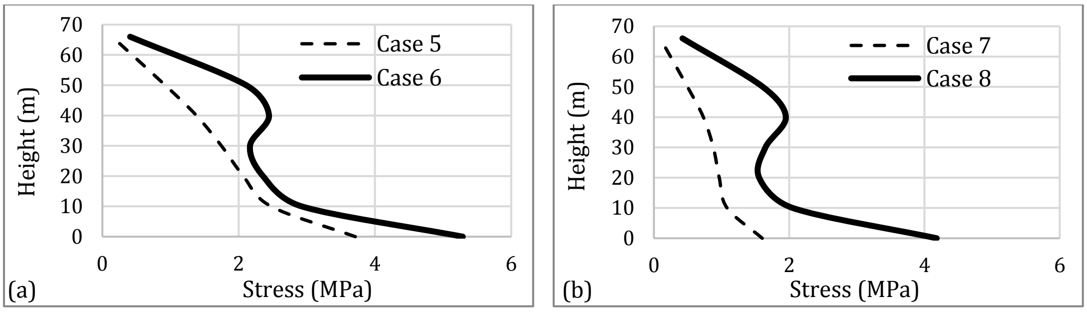

Fig. 10. Maximum principal stress change by height for dam-foundation interaction: (a) Without gravity; (b) With gravity.

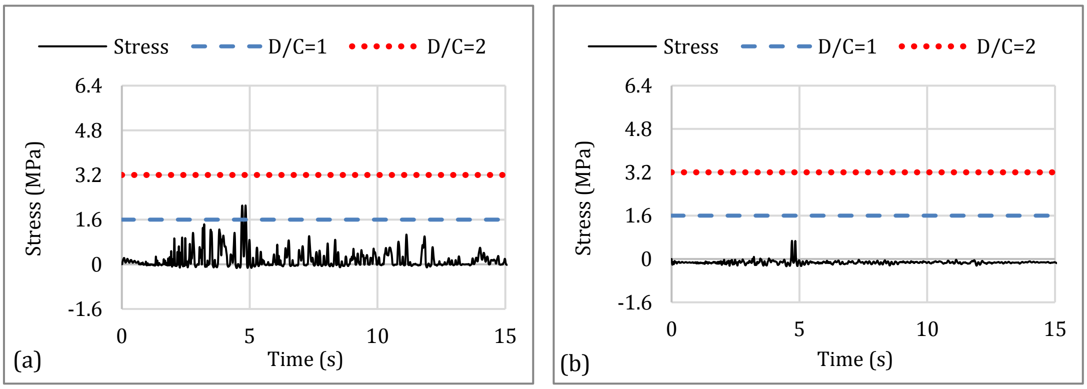

Fig. 11. Maximum principal tensile stress change by time for empty reservoir condition considering dam body: a) Case 1; b) Case 3.

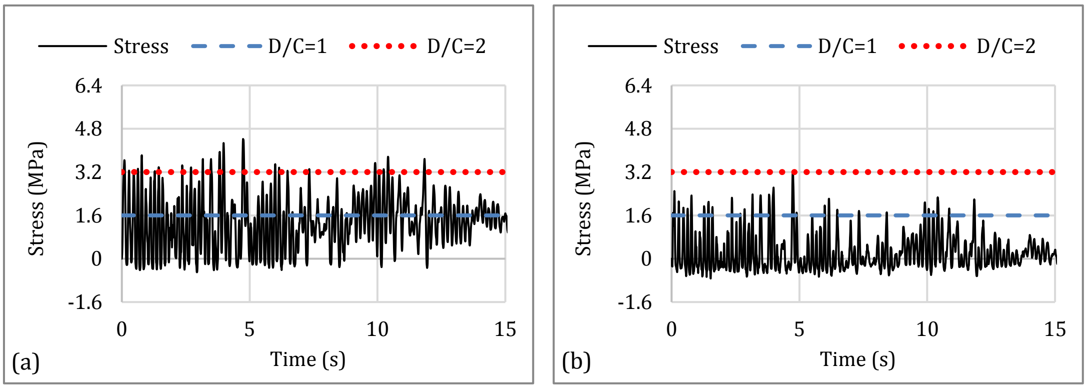

Fig. 12. Maximum principal tensile stress change by time for full reservoir condition considering dam body: a) Case 2; b) Case 4.

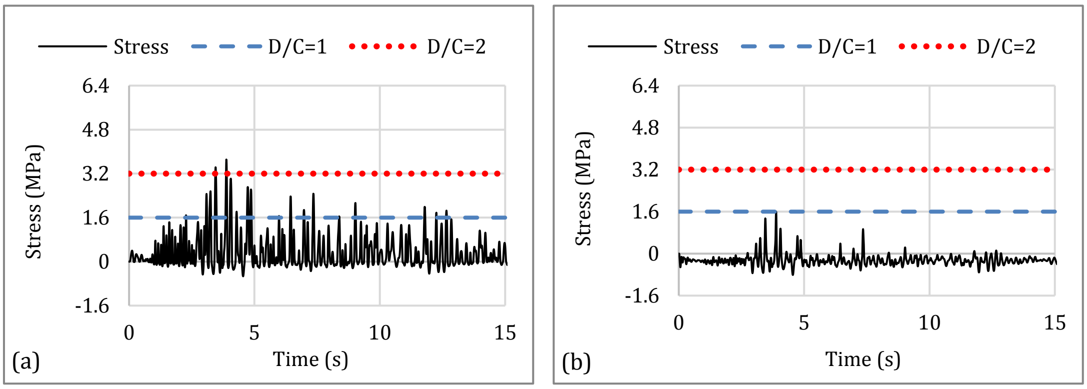

Fig. 13. Maximum principal tensile stress change by time for empty reservoir condition considering dam and foundation rock interaction model: a) Case 5; b) Case 7.

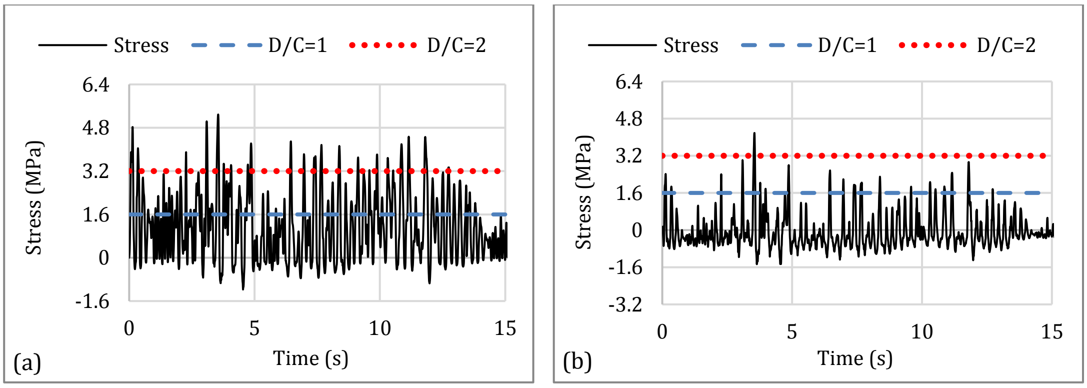

Fig. 14. Maximum principal tensile stress change by time for full reservoir condition considering dam and foundation rock interaction model: (a) Case 6; (b) Case 8.

Performance curves were drawn to determine the earthquake performance of Akçakoca RCC Dam concrete according to linear time history analysis. The earthquake performance of the dam is high when the reservoir is empty and gravity is included. Neglecting the gravitational acceleration reduces the earthquake performance and exceeds the acceptable level in both the empty reservoir case and the full reservoir case. It completely exceeds this level when the reservoir is full and gravitational acceleration is neglected. Analyzes under the influence of full reservoir and gravitational acceleration are given in Figs. 15 and 16. As seen in Fig. 16a, it falls below the accepted curve in the range of 1.3-1.4 in the dam body analysis (Case 4). A similar situation is shown in Fig. 16b. In the case of the dam body and bedrock (Case 8), it falls below the accepted curve in the range of 1.4-1.5. According to linear analysis, damage in the selected point of the concrete seems inevitable since the performance curves are generally above the acceptance curve in both cases.

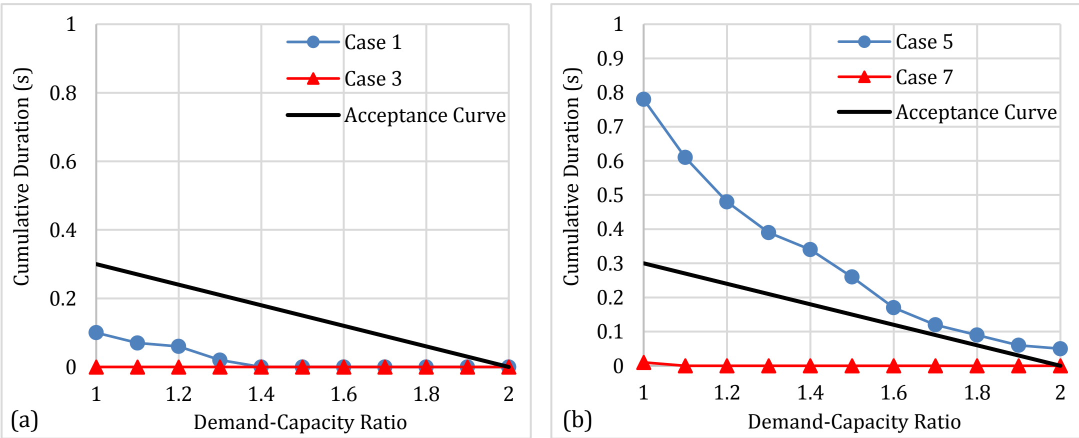

Fig. 15. Performance assessment of empty dam models: a) Only dam body; b) Dam and foundation rock interaction.

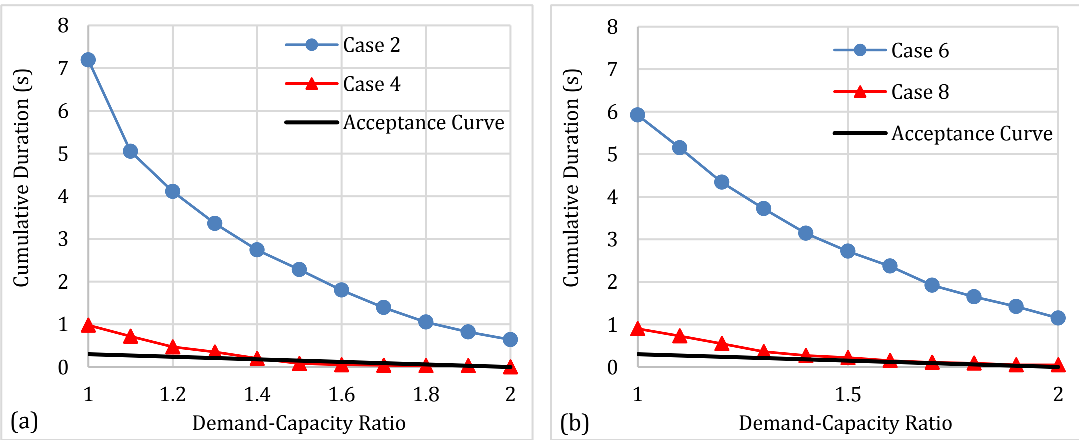

Fig. 16. Performance assessment of full reservoir condition:
a) Only dam body model; b) Dam and foundation rock interaction models.

6. Conclusions

This study explores the seismic behavior and performance of the Akçakoca Roller Compacted Concrete (RCC) Dam through a two-dimensional analysis, considering the interaction between the dam and the reservoir. The representation of reservoir water employs finite elements through the Eulerian-Lagrangian coupled (CEL) approach. Dam models undergo analysis for both horizontal and vertical earthquake components, examining scenarios with and without the influence of gravity.

The numerical analyses clearly demonstrate that the presence of reservoir water significantly influences the earthquake response of the dam. Linear analyses show increased displacements and principal stresses due to hydrodynamic pressure. The earthquake performance assessment of the Akçakoca RCC Dam indicates that substantial damage may occur in the concrete, as revealed by linear time-history analyses in both empty and full reservoir cases. The linear analysis results further demonstrate that the level of damage increases with hydrodynamic pressure. The inclusion or neglect of gravitational acceleration in the analyses leads to notable differences in tensile stresses. In analyses incorporating gravitational force (Cases 3, 4, 7, 8), principal tensile stresses in the dam body are lower for both empty and full reservoir scenarios compared to other analyses (Cases 1, 2, 5, 6). Similar differences are observed in the performance analysis. Under the influence of gravity and in the empty condition, analyses (Cases 3, 7) result in the performance curve falling below an acceptable level, while in other analyses, concrete damage appears inevitable.

Based on the findings of this study, the following suggestions can be clearly outlined:

- It has been observed that gravity effect should be considered as a pre-condition before seismic analyses,
- In assessing the earthquake performance of the RCC dam, it is crucial to model the dam body and foundation rock together.
- Considering hydrodynamic pressure is crucial in earthquake performance analyses to obtain more critical and accurate results.
- Conducting nonlinear analyses is recommended to assess the earthquake performance of an RCC dam more reliably, especially after incorporating the effects of gravity in the analyses.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

REFERENCES

ABAQUS (2014). Version 6.14. ABAQUS user's manual, Dassault Systèmes, SIMULIA.

AFAD (2023). Department of Disaster and Emergency, Ministry of Internal Affairs, Türkiye. https://deprem.afad.gov.tr/content/131 [accessed 01-11-2023].

Alebmbagheri M (2016). Earthquake damage estimation of concrete gravity dams using linear analysis and empirical failure criteria. *Soil Dynamics and Earthquake Engineering,* 90, 327–339.

Bathe KJ (1996). Finite Element Procedures. Prentice Hall Upper Saddle River, New Jersey 07458.

Bayraktar A, Kartal ME, Basaga HB (2009). Reservoir water effects on earthquake performance evaluation of Torul concrete-faced rockfill dam. *Water Science and Engineering*, 2(1), 43-57.

Benson DJ (1997). A mixture theory for contact in multi-material Eulerian formulations. *Computer Methods in Applied Mechanics and Engineering*, 140, 59-86.

Benson DJ, Okazawa S (2004). Contact in a multi-material Eulerian finite element formulation. *Computer Methods in Applied Mechanics and Engineering,* 193, 4277-4298.

Calis G, Yıldızel S (2019). Investigation of roller compacted concrete: Literature review. *Challenge Journal of Concrete Research Letters*, 10(3), 63-74.

Cervera M, Oliver J, Prato T (2000). Simulation of construction of RCC dams, I: Temperature and aging. *Journal Structural Engineering,* 126(9), 1053-1061.

Dou SQ, Li JJ, Kang F, (2019). Health diagnosis of concrete dams using hybrid FWA with RBF-based surrogate model. *Water Science and Engineering,* 12(3), 188-195.

DSİ (2023). General Directorate of State Hydraulic Works, Ministry of Agriculture and Forestry, Türkiye. https://dsi.gov.tr/Galeri/ResimGaleriDetay/608 [accessed 01-11-2023].

Erdik M (2000). Report On 1999 Kocaeli and Düzce (Türkiye) Earthquakes. Bogaziçi University-Department of Earthquake Engineering. http://www.koeri.boun.edu.tr/earthqk/earthqk.html [accessed 01-11-2023].

Hariri-Ardebili MA, Seyed-Kolbadi SM, Kianoush MR (2016). FEM-based parametric analysis of a typical gravity dam considering input excitation mechanism. *Soil Dynamics and Earthquake Engineering*, 84, 22–43.

He JP, Jiang ZX, Zhao C, Peng ZQ, Shi YQ (2018). Cloud-Verhulst hybrid prediction model for dam deformation under uncertain conditions. *Water Science and Engineering,* 11(1), 61-67.

Hongwei L, Wang L, Pei L, Chen J, Lu X, Deng D (2023). An advanced method for evaluating the cracking risks of gravity dams during the construction period considering the uncertainty of thermodynamic parameters. *Structures,* 53, 537–549.

Huang J (2018). An incrementation-adaptive multi-transmitting boundary for seismic fracture analysis of concrete gravity dams. *Soil Dynamics and Earthquake Engineering,* 110, 145–158.

Kartal ME, Cavusli M, Sunbul AB (2017). Assessing seismic response of a 2D roller-compacted concrete dam under variable reservoir lengths. *Arabian Journal of Geosciences,* 10: 488.

Kartal ME, Karabulut M (2018). Earthquake performance evaluation of three-dimensional roller compacted concrete dams. *Earthquakes and Structures*, 14(2), 167-178.

Li Z, Wu Z, Chen J, Pei L, Lu X (2021). Fuzzy seismic fragility analysis of gravity dams considering spatial variability of material parameters. *Soil Dynamics and Earthquake Engineering,* 140, 106439.

Li Z, Wang L, Luo Z (2022). A feature-driven robust topology optimization strategy considering movable non-design domain and complex uncertainty. *Computer Methods in Applied Mechanics and Engineering*, 401, 115658.

Liu Y, Wang L, Li M, Wu Z (2022). A distributed dynamic load identification method based on the hierarchical-clustering-oriented radial basis function framework using acceleration signals under convex-fuzzy hybrid uncertainties. *Mechanical Systems and Signal Processing*, 172, 108935.

Luo DN, Hu Y, Li QB (2016). An interfacial layer element for finite element analysis of arch dams. *Engineering Structures,* 128, 400-414.

Sharma V, Fujisawa K, Murakami A (2020). Space–time FEM with block-iterative algorithm for nonlinear dynamic fracture analysis of concrete gravity dam. *Soil Dynamics and Earthquake Engineering,* 131, 105995.

Skrzat A (2012). Application of coupled Eulerian-Lagrangian approach in metal forming simulations. *Zeszyty Naukowe Politechniki Rzeszowskiej*, Nr 284, *Mechanika z*. 84 (4/12).

Subrata M, Damodar M (2014). Experimental investigation on nonlinear dynamic response of concrete gravity dam-reservoir system. *Engineering Structures,* 80, 289–297.

Sunbul AB, Mungan H, Sünbül F, Kartal ME (2018). Investigation of seismic behavior of a clay core rock fill dam using finite element method. *Eurasian Journal of Civil Engineering and Architecture,* 2(1), 7-16.

Wang G, Wang Y, Lu W, Zhou C, Chen M, Yan P (2015). XFEM based seismic potential failure mode analysis of concrete gravity dam–water–foundation systems through incremental dynamic analysis. *Engineering Structures*, 98, 81–94.

Wang L, Zhao Y, Liu J, Zhou Z (2023). Uncertainty-oriented optimal PID control design framework for piezoelectric structures based on subinterval dimension-wise method (SDWM) and non-probabilistic time-dependent reliability (NTDR) analysis. *Journal of Sound and Vibration,* 549, 117588.

Wilson EL, Khalvati M (1983). Finite elements for the dynamic analysis of fluid-solid systems. *International Journal Numerical Methods Engineering,* 19, 1657–1668.

Yang J, Qu XD, Chang M (2019). An intelligent singular value diagnostic method for concrete dam deformation monitoring. *Water Science and Engineering,* 12(3), 205-212.

Yin P, Wang K, Chen L, Zhang Y, Yang K, Wang J (2023) Horizontal Bearing Capacity and Reliability of Piles in Coastal Soft Soil Considering the Time-Varying Characteristics. *Journal of Marine Science and Engineering,* 11(2), 247.

Zhang MX, Li MC, Shen Y, Ren QB, Zhang JR (2019). Multiple mechanical properties prediction of hydraulic concrete in the form of combined damming by experimental data mining. *Construction and Building Materials,* 207, 661-671.