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Numerical analysis of the Dukan dam under the influence of assumed seismic loads

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Abstract. Dukan dam is an important hydraulic structure in Iraq used for water storage, flood control, and electricity generation. During earthquakes, this dam can be subjected to varying degrees of damage depending on the intensity and duration of the seismic event. In this article, Dukan dam will be analyzed during an assumed earthquake using the ABAQUS software. The behavior of the dam under the seismic load will be investigated. In this process, a two-dimensional finite element model of the central part of the dam, containing the maximum dam height, was created, taking into account the geometric parameters of the model, types of finite elements, material models, and boundary conditions. An analysis was performed for the dam section using the static analysis, seismic effect analysis, and hypothetical failure zones of the dam were identified.

1 Introduction

Dukan dam formed upon Lesser Zab River; one of the Tigris River tributaries in Iraq. The Dukan dam was built between 1954 and 1959 as a multi-purpose dam to provide water storage, irrigation and hydroelectricity. Concrete gravity dams serve as essential infrastructure assets that play a key role in a variety of sectors, including flood damage reduction, hydroelectric power generation, navigation, and water supply. The stability of these robust concrete structures relies on factors such as their geometric shape, mass, and the strength of the concrete used in their construction. The failure of these dams, particularly in regions prone to earthquakes, can result in severe consequences with substantial social and economic repercussions. In regions prone to seismic activity, where earthquake intensity varies across different zones, it is imperative to follow specific criteria when designing and evaluating concrete gravity dams for earthquake loading to ensure their safety and structural integrity [4].

The impact of seismic events on concrete gravity dams can be significant, particularly when considering factors like earthquake intensity and duration. While traditional design strategies for many dams worldwide have typically focused on lateral static forces induced by earthquakes, a comprehensive understanding of how these structures behave under realistic three-dimensional earthquake forces only emerged with the development of more accurate methods for addressing dynamic responses [13].

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During earthquakes, concrete gravity dams may experience damage in various forms, with cracking being a common issue observed in their structures. Contributing factors to cracking include subpar construction quality, material fatigue, and deterioration over time. It is crucial to employ proper methods for damage analysis to accurately assess the extent of structural damage and implement timely repair strategies to uphold structural integrity [20].

Engineers often rely on visual inspection techniques and computer simulations and non-destructive testing methods for conducting damage analysis in concrete gravity dams. By using these techniques effectively, they can pinpoint areas of concern within the structure and devise suitable repair approaches for addressing cracks and damages sustained during seismic events [16].

Examining case studies of concrete gravity dam failures during earthquakes offers valuable insights into the vulnerabilities of such structures under seismic forces. Through studying these failures, engineers can refine their understanding of potential failure modes and develop predictive models for assessing the seismic performance of concrete gravity dams to mitigate potential catastrophic consequences [14].

The purpose of this work is to obtain a two-dimensional finite element model of the critical section in Dukan dam and to assess its seismic stability, stress distribution and possible failure parts.

2 General description of Dukan dam

Dokan Dam is located on the Lesser Zab river approximately 295km north of Baghdad and 65km southeast of Sulaimaniyah city. The dam is a concrete arch with gravity abutment blocks located in a narrow steep sided gorge incised in the limestone and dolomite bedrock [12].

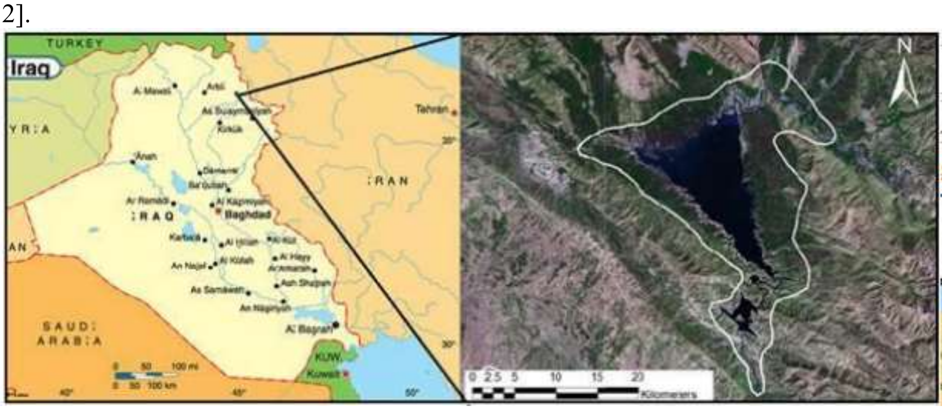


Fig. 1. Dukan dam and reservoir location.

The crest length of the dam 360m, height 116.5m, Radius of Upstream Face Cylinder: 120m, Top road width:8.42m, Top crest width: 6.2m, Width at Base Including Foundation Socle 65.0 m, Width at Base Without Foundation Socle 34.3 m , Crest Level (Lowest) El. 516.07 m ASL, Maximum Recorded, Reservoir Level El. 512.56 m ASL on 04/05/1988, Minimum Recorded Reservoir Level El. 430.95 m ASL on 25/12/1960, Design :British engineer 1930-1954, Implement:French company 1954-1959, Hydropower:Russian company1973-1979 [3] [17].

Fig. 2. Dukan dam.

3 Regional seismicity

Dukan Dam lies in a folded nappe zone to the southwest of the plate boundary where the Arabian tectonic plate is being subducted beneath the Persian plate [1]. The earthquakes that occurred in the dam area or nearby areas were searched for by the USGS. The seismic data in the Dukan dam area was surveyed from the date of its construction to 2024, and through the results it was found that the maximum earthquake near the Dukan dam occurred surface-wave magnitude of 5.8 on December 12, 1980 [10].

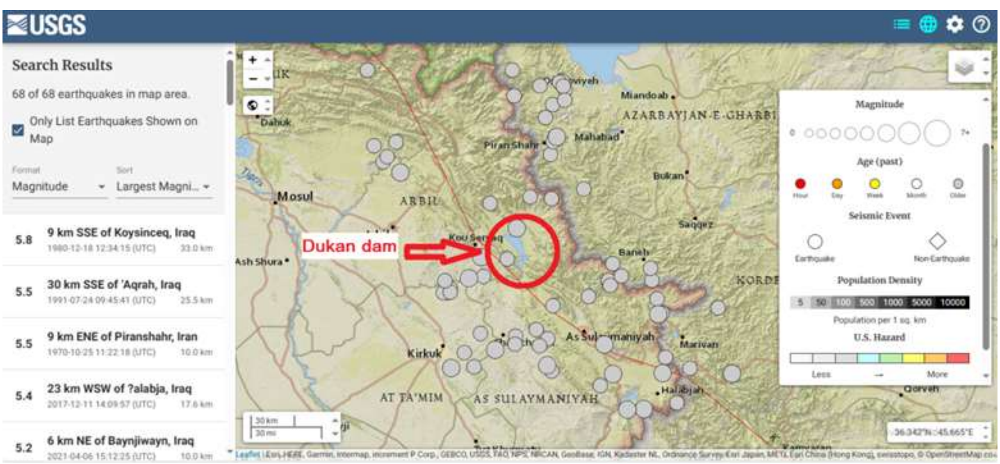


Fig. 3. Map of earthquakes in the dam region.

4 Computer simulation analysis

Computer simulations have become an increasingly powerful tool for analyzing and understanding concrete structures. In the context of Concrete Gravity Dams, these simulations can help identify potential areas of weakness and predict behavior under various conditions.

One of the most significant benefits of using computer simulations for crack analysis is the ability to simulate different scenarios without causing any actual damage to the structure itself. This allows engineers to test different repair and maintenance strategies, ensuring the most effective course of action is taken [5][19].

To perform these simulations, advanced software tools are required that utilize finite element analysis (FEA) techniques. FEA involves breaking down the complex geometry of the structure into smaller, simpler elements, allowing for more accurate analysis of stress and strain distributions.

Advanced simulation tools for analysis modeling software, such as ABAQUS, can accurately simulate the behavior of Concrete Gravity Dams under various conditions. These tools allow engineers to visualize stress and strain distributions and potential crack propagation paths and evaluate the effectiveness of different maintenance strategies. Through the use of computer simulations for crack analysis, engineers can ensure the safety and longevity of hydraulic structures, minimizing the potential for catastrophic failures and preserving the integrity of these essential infrastructure components [2] [6].

5 Creating a model in ABAQUS

To create a finite element model and perform calculation, the SIMULIA ABAQUS software package was selected.

When calculating the impact of earthquakes, it is necessary to take into account the nonlinear operation of the material. For numerical modeling of concrete and other brittle materials in any structures, the ABAQUS program uses the Concrete Damage Plasticity (CPD) model, which allows taking into account the peculiarities of concrete behavior under variable loads [9] [15].

A two-dimensional section was designed for the central part of the entire dam, which has the maximum height of the dam, and the values of hydrostatic water pressure and seismic loads were entered.

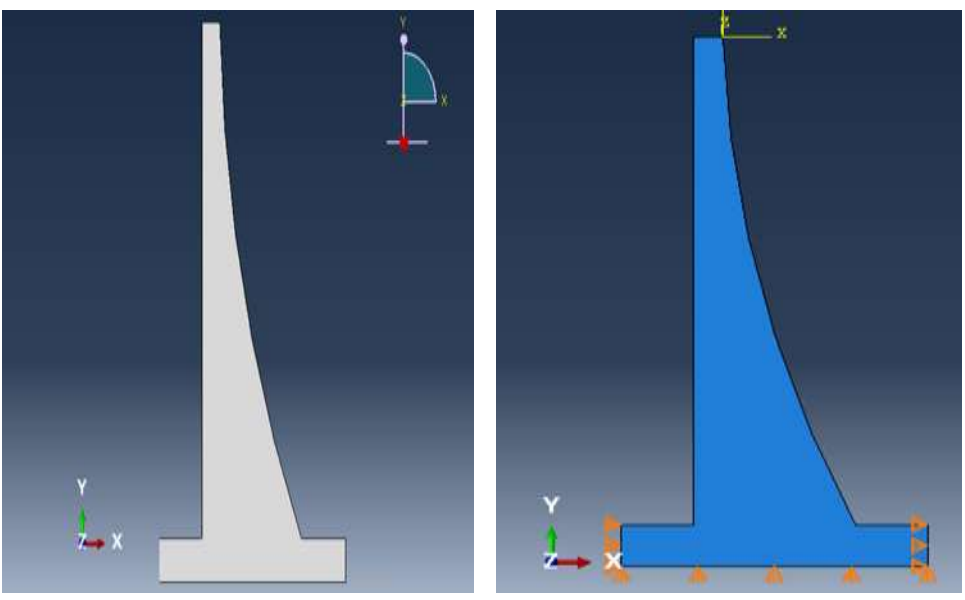


Fig. 4. In program ABAQUS (a) A section of the Dukan dam at the greatest height, (b) Dam foundation model.

6 Properties of materials

To create the model in the ABACUS program, the real dimensions of the dam were taken and as mentioned above in the General description of Dukan dam.

The properties of materials for the concrete are : density 2470 kg/m3, Young's modulus 32.5 GPa, Poisson's ratio 0.2, tensile strength 1.5 MPa, compressive strength 38 MPa, fracture energy 133 Nm/m2, and fracture toughness is 0.45 MPa/m.

7 Static and dynamic calculation

7.1 Static calculation of the system under hydrostatic load, taking into account its own weight

The static load takes into account the own weight of the structure and the hydrostatic pressure p [Pa] acting on the pressure face of the dam, equal to zero on the water surface and equal to $p = \rho w.g.h$+atmospheric pressure at the base of the plate, where ρw is the density of water [kg/m3], h is the height of the water [m], g is the acceleration of gravity [m\c2].

In the ABACUS program, values have been entered h =116.5 m. ρw = 1000 (kg/m3), g = 9.81 m/s2, and the atmospheric pressure is 100,000 Pa.

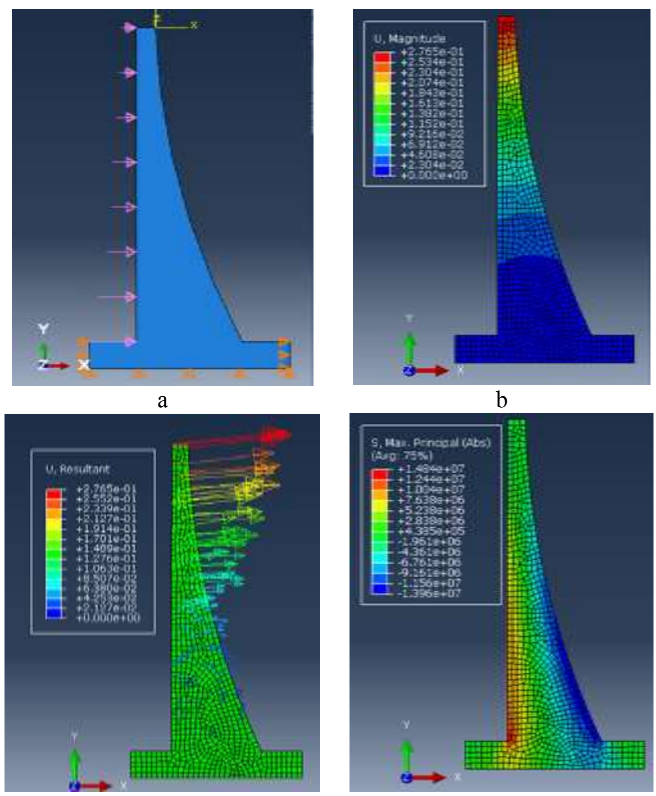


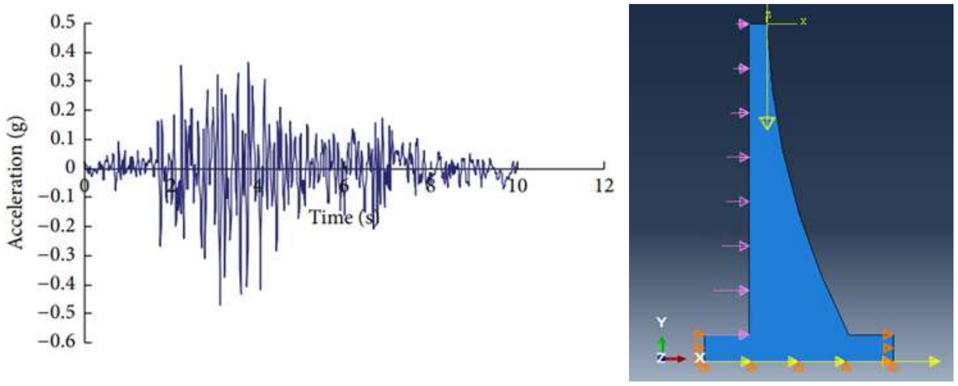
Fig. 5. In program ABAQUS under the influence of hydrostatic (a) Hydrostatic loads, (b) Displacements, (c) Direction of displacement, (d) Stresses distribution.

7.2 Dynamic calculation of the system under the influence of seismic load

Under dynamic load, we take into account the own weight of the structure and the hydrodynamic effect on the pressure face of the dam. The seismic impact is set as the horizontal and vertical accelerations of the dam sole. The concrete damage model provided by the abacus software can simulate concrete damage and dam failure behavior under earthquakes [8].

The Dukan dam was not affected by the earthquakes that occurred in previous years , and due to the increase in earthquakes in the area , it became important to know the behavior of the dam concrete under the influence of an earthquake with a greater degree than the earthquakes that occurred earlier from the area to predict the behavior of the dam and the distribution of stresses and displacements. So in this research, data were taken for a previous earthquake that occurred near the gravity dam in Koina. The Koina gravity dam is located on the Koina River in the west of the Indian peninsula, which was considered to be stable and nearly nonseismic, This area is somewhat similar to the area where the Dukan dam is located. The concrete gravity dam is 103 meters high and 70 meters wide at its base; when a magnitude 6.5 earthquake shook the area in 1967. The Koina earthquake was recoded with the maximum acceleration measured at the base gallery of 0.47 g in the normal horizontal direction of the axis of the dam. As a result of the earthquake , cracks appeared in the Koyna Dam concrete gravity dam located near this city [7] [18].

In this work, an Acceleration with a time interval of 10 seconds, digitized with an interval of 0.01, is used as a seismic effect.



a b

Fig. 6. In program ABAQUS (a) Seismic data, (b) Hydrostatic and seismic loads.

After entering the seismic and hydrostatic loads, the duration of the earthquake is 10 seconds, and the earthquake tensile data, the program analyzes them and displays the displacement results and directions as well as the results of the distribution of internal stresses during the duration of the earthquake.

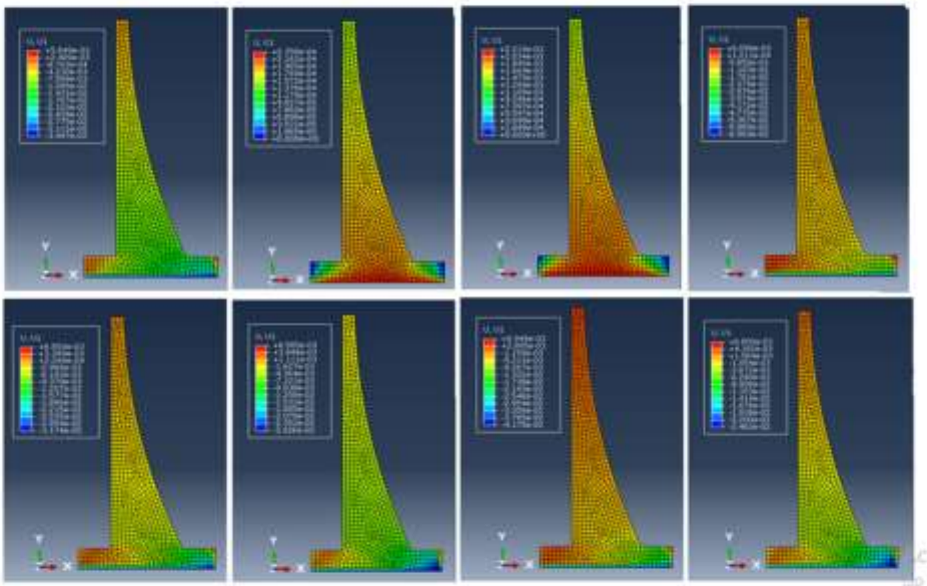


Fig. 7. Displacements under the influence of hydrostatic and seismic loads.

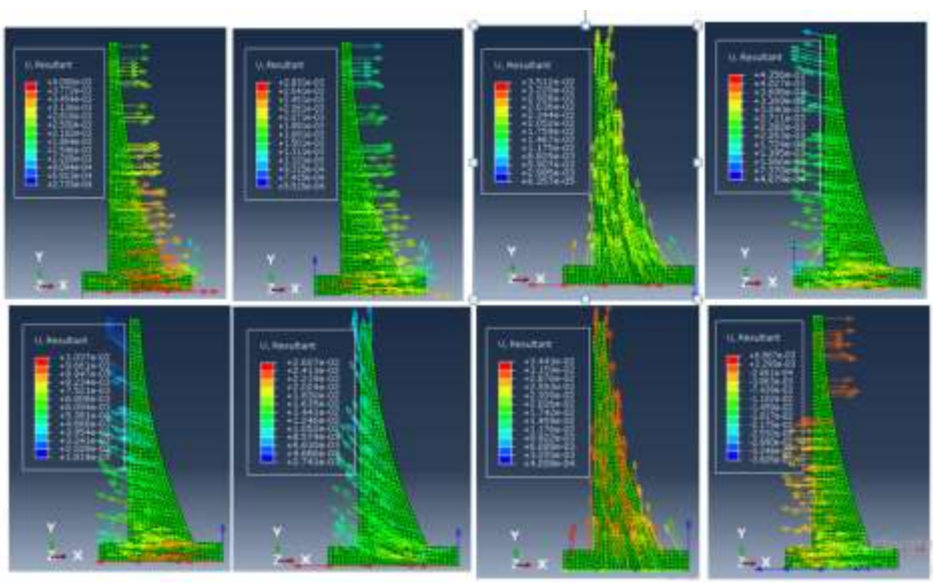


Fig. 8. Direction of displacement under the influence of hydrostatic and seismic loads.

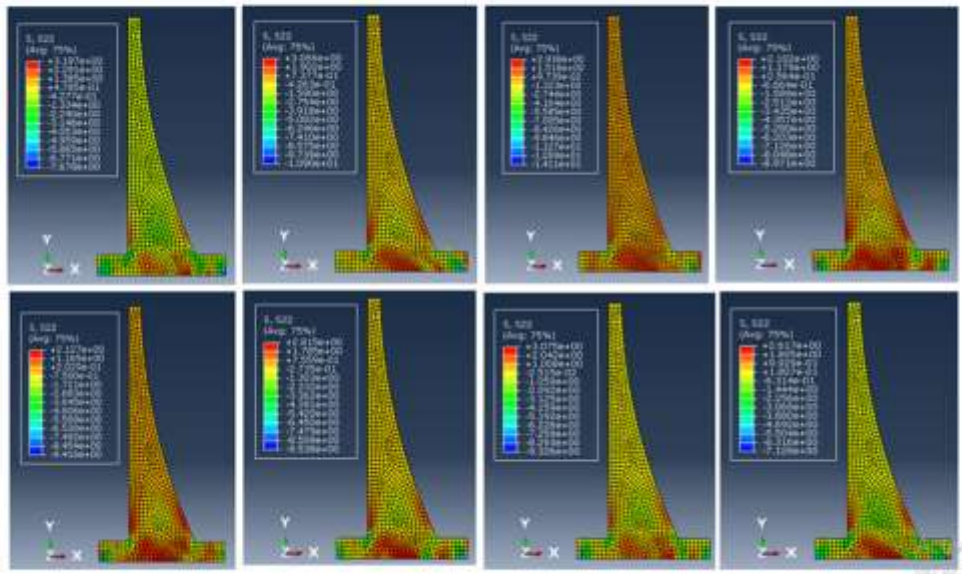


Fig. 9. Stresses distribution under the influence of hydrostatic and seismic loads.

It should be noted that the distribution of vertical, horizontal and total displacements, vertical, horizontal of the first main dam stress values under dynamic load for elastic and nonlinear materials differ much more than under static load. The nonlinear material allows us to consider the process of occurrence and development of cracks in the dam

The vulnerability of Dukan dam to seismic events is a critical factor that must be taken into account when evaluating it susceptibility to damage during earthquakes. Variations in concrete tensile strength across different areas of the dam can result in varying degrees of damage, emphasizing the significance of considering material properties when assessing the seismic resilience of gravity dams.

In the realm of seismic evaluation, nonlinear static pushover (SPO) and incremental dynamic analysis (IDA) have been employed to estimate both the structural capacity and performance of concrete gravity dam, by comparing the seismic demands placed on this structure with their actual capacity [11].

Additionally, it has been noted that ground motions originating near assumed fault lines can have a significant impact on the overall damage by Dukan dam. A refined evaluation model for Dukan dam damage indexes has been put forth to gauge the cumulative damage and energy characteristics resulting from various types of near the assumed fault ground motions.

8 Conclusion

When reviewing the results , the stresses obtained to which the Dukan dam is subjected due to hydrostatic and seismic loads, we observe the distribution of stresses in the dam body, with varying intensity during the seconds in which the earthquake occurs, depending on the severity of the earthquake, and the greatest stress is induced when the greatest intensity of the earthquake, and this is the opposite of the stresses resulting from the hydrostatic load, which is gradual during the filling stage of the dam reservoir and the arrival of water in the reservoir to the design level, and as we note in the result, the distribution of stresses the greatest stress is at the deepest point of the dam due to the highest water elevation.

As for the displacements occurring in the dam body due to hydrostatic and seismic loads, they are in different and irregular directions and values, which has a significant impact on the small cracks located inside the dam body, as it leads to an increase in the length of these cracks and increase the risk of dam failure.

According to the data obtained from USGS, the largest earthquake suffered by the Dukan dam area was a magnitude of 5.8 and there were no failures in the dam body and its resistance was good. The values of the seismic loads entered in the program at the Dukan dam, which was supposed to expose the dam area to an earthquake of magnitude 6.5, did not result and the dam's resistance to these loads was good, but there is a possibility of the development of small cracks in the dam body .

When analyzing the seismic behavior of concrete gravity dams, it is essential to take into account the material properties that impact their stability during earthquakes. The elastic modulus, Poisson's ratio, density, cohesion, and friction angle of both the dam body and its foundation are crucial in determining potential damage risks.

Furthermore, variability in material properties at the dam-foundation interface, such as friction coefficient and cohesion, can introduce uncertainties in seismic analysis. By incorporating normal distributions with average values and standard deviations for these parameters, researchers can address potential variations in soil-rock interactions that may impact dam stability during earthquakes.

In summary, integrating detailed material parameter data into numerical models for dynamic analysis offers valuable insights into how concrete gravity dams behave under seismic loading. By understanding how these parameters influence structural responses and failure mechanisms, engineers can develop more effective techniques for damage analysis and repair strategies to enhance the earthquake resistance of these critical infrastructure assets.

Assessing the seismic performance of concrete gravity dams is crucial for safeguarding these critical structures against earthquake-induced damage. By following robust analytical procedures and incorporating appropriate design criteria based on factors like material properties and seismic intensity levels, engineers can bolster the resilience of concrete gravity dams in earthquake-prone regions. Comprehending the influence of earthquake intensity on concrete gravity dams is vital for maintaining their structural integrity during seismic events. By integrating advanced analysis methods and empirical evidence, it is possible to strengthen the resilience of these critical hydraulic structures against potential seismic hazards. It is clear that seismic duration plays a crucial role in determining the extent of damage sustained by concrete gravity dams during earthquakes. Understanding this influence is vital for devising effective strategies to mitigate damage and ensure the security and resilience of these essential infrastructure systems.

Prioritizing high-quality construction methods and rigorous materials testing is key to bolstering the resilience of concrete gravity dams against earthquake-induced damage, thereby guaranteeing their continual functionality and safety. Non-destructive testing methods are indispensable for evaluating the seismic performance of concrete gravity dams and identifying areas of concern. Through a combination of visual inspections and advanced technologies like GPR, ultrasonic testing, and acoustic emission testing, engineers can comprehensively understand a dam's condition and make informed decisions regarding maintenance and repair strategies. Constructing resilient predictive models for the seismic performance of concrete gravity dams demands a holistic approach that addresses parameter uncertainty, seismic input data, natural vibration characteristics, progressive failure analysis, CAV capacity evaluation, and displacement histories. By integrating these components into predictive modeling procedures, engineers can enhance the resilience of concrete gravity dams against damage caused by earthquakes.

References

1- T. Onur, R. Gok, W. Abdulnaby, H. Mahdi, N. Numan, H. Al-Shukri, A. Shakir, H. Chlaib, T. Ameen, N. Abd, Seismological research letters **88(3)**, 798-811 (2017)

2- R. Das, P. Cleary, International Journal of Fracture **179**, 9-33 (2013)

3- M. Hindreen, *University of gaziantep Graduate school of natural & applied sciences* (2016)

4- M. Akhmedov, K. Saliamova, Bulletin of the Belgorod State Technological University named after V.G. Shukhov **5**, 91-94 (2015)

5- I. Fedorov, The methodology of modeling concrete hydraulic structures taking into account nonlinear deformation under seismic influences: disser (All-Russian Scientific Research Institute of Hydraulic Engineering named after B.E. Vedeneev, St. Petersburg, 2020)

6- I. Fedorov, Proceedings of the All-Russian Scientific Research Institute of Hydraulic Engineering named after B.E. Vedeneev **295**, 21-30 (2020)

7- A. Mansouri, M. Neshaei, R. Aghajany, Journal of Applied Sciences and Environmental Management **2**, 317-325 (2011)

8- T. Saksala, J. Mäkinen, Procedia Structural Integrity **28**, 784-789 (2020)

9- S. Ya, S. Eisenträger, Y. Qu, J. Zhang, T. Kuen, C. Song, Soil Dynamics and Earthquake Engineering **164**, 107620 (2023)

10- United States of America Geological Survey (USGS), https://www.usgs.gov/programs/earthquake-hazards

11- B. Najmal-Dini, A. GhezelSofloo, K. Bina, Journal of Engineering and Higher Technology (JEHT) **2(2)**, 1-10 (2016)

12- V. Sissakian, A. Abdul-Ahad, N. Al-Ansari, R. Hassan, S. Knutsson, Journal of Earth Sciences and Geotechnical Engineering **6**, 35-63 (2016)

13- H. Ali, M. Alam, M. Haque, M. Alam, Natural Resources **3(1)**, 18-28 (2012)

14- A. Abraham, *Louisiana State University and Agricultural and Mechanical College* (2020)

15- G. Wang, Y. Wang, W. Lu, M. Yu, C. Wang, Engineering Structures **148**, 263-276 (2017)

16- M. Alembagheri, M. Ghaemian, Earthquake Engineering & Structural Dynamics **42**, 123-144 (2013)

17- R. Hassan, N. Al-Ansari, S. Ali, A. Ali, T. Abdullah, S. Knutsson, Iraq. published by Engineering **8(9)**, 582-596 (2016)

18- A. Tidke, Adhikary S (2021) Seismic fragility analysis of the Koyna gravity dam with layered rock foundation considering tensile crack failure. Engineering Failure Analysis, vol. 125, 105361

19- Hussein T, Ab-Kadir M, Ramli M (2024) A Numerical Investigation of Seismic Load Analysis for a Concrete Gravity Dam Utilizing Abaqus Software. Journal of Electrical Systems, vol. 20, pp. 818-831

20- N. Adamo, N. Al-Ansari, V. Sissakian, J. Laue, S. Knutsson, Journal of Earth Sciences and Geotechnical Engineering **10(6)**, 79-132 (2020)