Article

On the Analysis and Assessment of Large Concrete Dam Using Finite Element Approach

Ramzi M. Abduallah[1], **Moad Mohamed Alosta**[2], **Syamsul Bahri**[3,*]

[1] Ph.D candidate, Department of civil, environmental, and geodetic engineering, Ohio state university, United States; abduallah.2@osu.edu
[2] Department of Civil and Environmental Engineering, College of Engineering and Architecture, University of Nizwa, Birkat-al-Mouz, 616, Nizwa, Sultanate of Oman; Moad.alosta@unizwa.edu.om
[3] Department of Civil Engineering, Lhokseumawe State Polytechnic, Lhokseumawe 24301, Indonesia;
* **Correspondence:** syamsul_b62@yahoo.com

Manuscript received: 03-10-2021, revised: 29-10-2021, accepted: 12-11-2021.

Abstract

Assessment and evaluation of dam structure are one of the essential components in sustainable hydraulic engineering. Several countries all around the world have given essential attention to evaluating dam structures due to seismic loading and earthquake vulnerability. Hence in the current study, gravity dam failure is studied based on the possibility of overturning or sliding. For this purpose, the potential of the finite element (FE) models is adopted for the analysis using the LUSAS modeler. The modeling procedure was adopted following several protocols of dam design reported in the literature. The modeling procedure was established to have a better understanding of the relationship of crown displacement against the water level concerning the No uplift, uplift-drain effective, and uplift-drain ineffective. The research finding results showed that the maximum deformation in the dam structure foundation with load case 1 at 100 m water level and the displacement in structure foundation with load case 1 at 80 m water level.

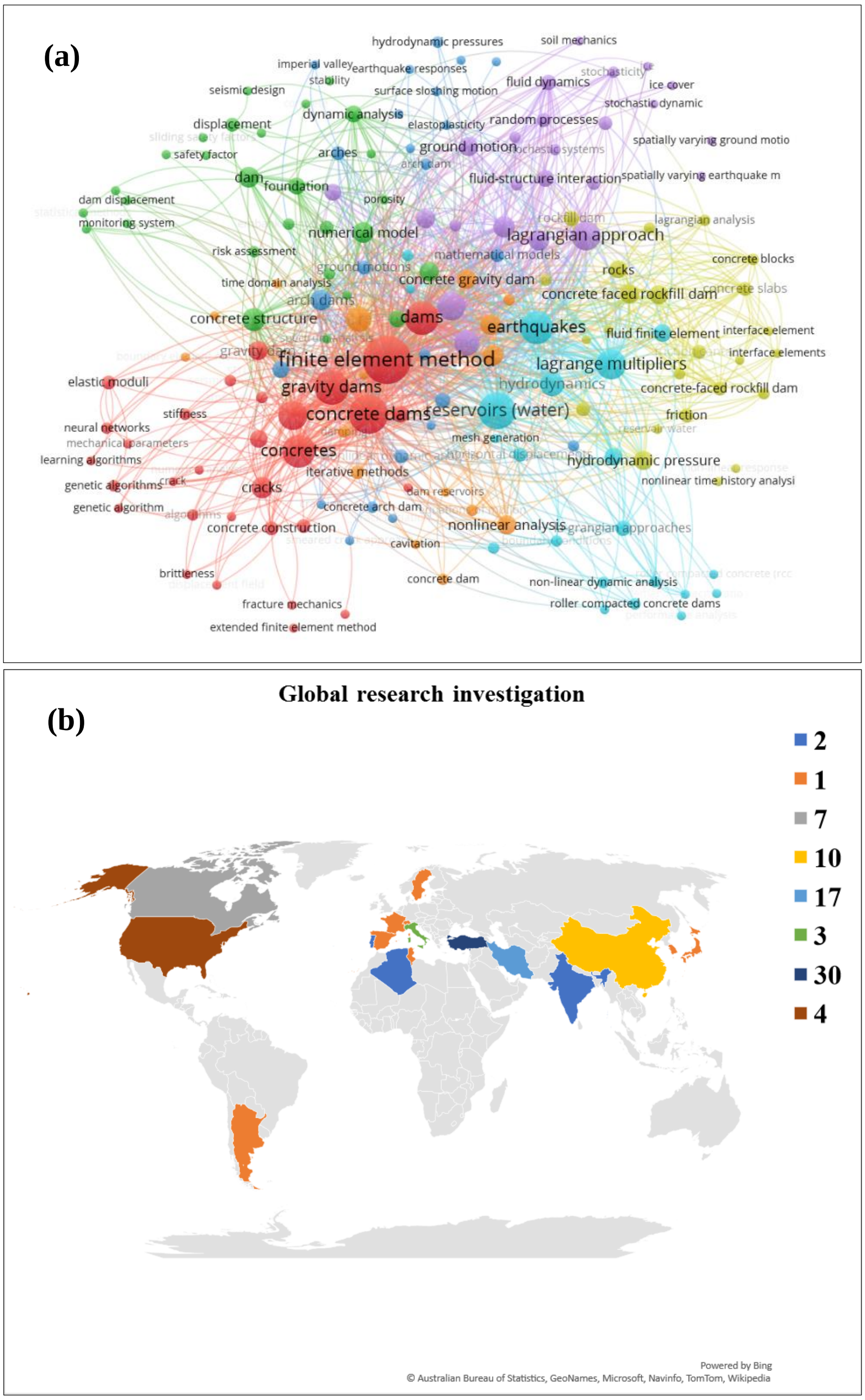
Keywords: Finite element; gravity dam; sustainability; dam failure; engineering structure.

1. Introduction

The size of concrete dams can serve as a basis for distinguishing them from other structures; they are also peculiar in terms of their bottom sediments, the foundation region, and their interactions with the reservoir water [1], [2]. In the field of dam engineering, one of the most important aspects is the systematic identification of concrete dams [3]. In most identification systems, the basic parameters are normally the measured structural responses of the dam under dynamic excitation [4]. The major reason for dynamic testing is to aid the identification of the major dynamic attributes of concrete dams that will facilitate the updating of their numerical models [5]. These updated models are then used for the prediction of the system response under severe seismic excitations. This involves the use of both ambient vibration and forced vibration tests [6]. Regarding the ambient vibration tests, they rely on environmental excitations for the measurement of the mode shapes, natural frequencies, & modal damping factors. Forced vibration test requires the use of mechanical exciters to generate sinusoidal forces. Accurate control of the excitation force aids the determination of the force–response relations that facilitate a better estimation of the modal properties. Other methods, such as moving mass exciters, and explosions near a dam can also be used to perform forced vibration tests as they allow periodic excitation forces in any direction.

It is worth surveying the established global research over the literature using the Scopus database. Figures 1a, b, and c reported the major keywords, countries, and the number of citations per region. The literature indicated there were over 70 research articles were published on concrete dams using finite element methods. The analysis was majorly adopted on the dam displacement, earthquake influence, hydrodynamic pressure, stochastic dynamic, safety factor, and several others. Based on the region investigation, Turkey and Iran were the major countries where the research was mainly conducted. This is due to the fact; those two countries experience a high risk of earthquakes. The same reputation of citation was observed for Turkey and Iran. By recalling the literature, the study by [7] reported a finite elemental analysis-based determination of the characteristics of the Fei-Tsui arch dam based on the seismic response ambient vibration data with the consideration of the reservoir water level effect. Furthermore, ambient vibration tests were used by [6] to measure the modal properties of a concrete gravity dam for further usage in the validation of a finite element model of the dam–reservoir–foundation system. Finite element analysis was also used by [8], [9] on the

Mauvoisin arch dam to perform a continuous ambient vibration-recording program; the outcome of the study showed a shift in the resonance frequencies with increases in the reservoir water level. The outcomes of finite element models on two arch dams using the ambient vibration tests were verified by [10] through comparison with the attributes of the actual as-built dams. The study by Alves & Hall relied on forced vibration tests to evaluate the modal properties of the Pacoima arch dam; the study also captured the seismic record of the structure based on finite element modelling [11]. Fedele et al [12] presented an overall inverse methodology for the identification of the elastic moduli in concrete arch-gravity dams; the approach relied on the use of hydrostatic loading, finite element model-trained neural networks, and measurements using conventional monitoring instruments. The capacity of the integration of FEM with machine learning models was adopted for dam displacement monitoring [13]. The research was established to use spatial and temporal datasets for the simulation process. The proposed methodology gave a robust and reliable tool for concrete dam detection and sustainability. For more information about the concrete dam and sustainability readers can refer to the recently reported review research [14].



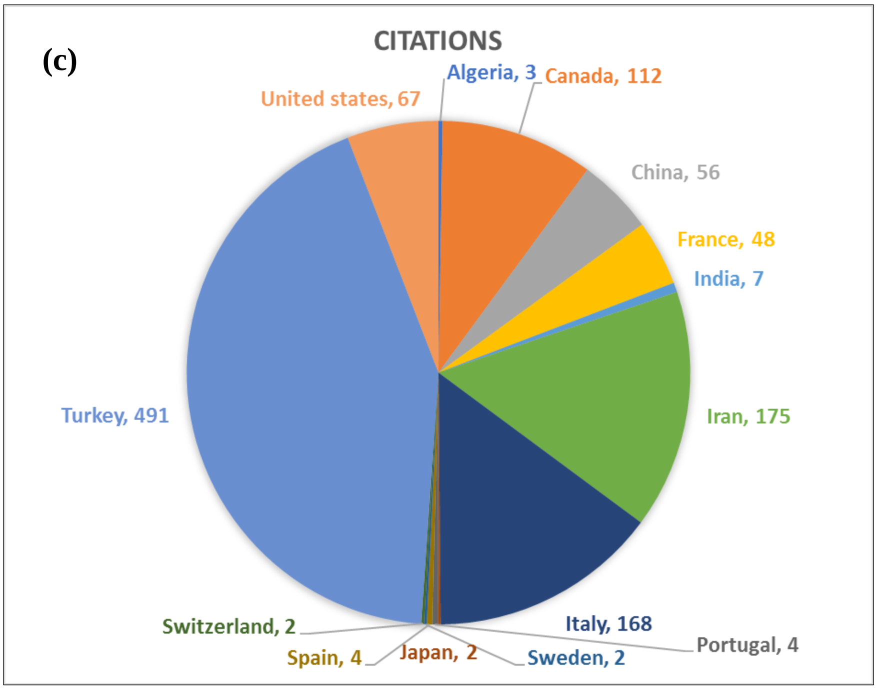


Figure 1. The reported literature review in the Scopus database. a) the major keywords, b) the global countries, c) the number of citations for the conducted research.

Among the factors that can affect the outcome of dynamic tests in dam engineering include the dam–reservoir interaction (affects the modal characteristics), the effect of energy absorption on the dam sediments, as well as dam–foundation interaction that can be characterized by inhomogeneity, anisotropy, etc. [15]–[18]. These factors are normally considered using either simple or complex numerical methods and the most popular method for modelling dam structure is the finite element method (FEM) [19].

In civil engineering applications, safe and cost-effective materials are necessary for achieving competitive and sustainable growth [20]. Some aspects of this research have been addressed by the thematic network on the integrity assessment of large concrete dams (NW-IALAD) by addressing various aspects of dam integrity, such as a review of the performance and maintenance of dams, rehabilitation, and repair of dams, the current safety assessment measures and dam-related computations in different European countries, as well as a methodological comparison of improved numerical simulation models of the structural features of concrete dams [12], [21]. The current research was established to have a better understanding of concrete dam sliding possibility by the water pressure. The contribution of the study focused on the investigation of the different cases of uplift pressure. For doing this, the assessment of the performance of LUSAS software was used for the dam analysis.

2. Description of Finite Element Method (FEM)

Richard Courant developed the Finite Element Analysis in 1943 in furtherance of the Ritz method of numerical analysis and vibrational calculus minimization for the calculation of the approximate solutions to vibration systems. Later in 1956, the detailed approach to the numerical analysis was published [22], with a focus on the "stiffness and deflection of complex structures". The mainframe computers were the only available computer systems in the early ’70s for carrying out Finite Element Analysis and they were generally owned by the aeronautics, nuclear, automotive, and defence industries. However, the recent advancements in technology have crashed the cost of computer systems, thereby increasing their processing capability [23]–[25]. These days, the capabilities of the FEM have advanced from what they used to be in the 70s as they can now perform accurate structure analysis [26].

The interaction between the foundation and dam body has a potential effect on the dynamic response and thus it shall be taken into the consideration. The concept of the finite element discretization that is based on the differential formulation expressed the displacement of the dam structure using the following formula [27]:

$$M_s\ddot{u} + C_s\dot{u} + K_s u = F_g + F_p \tag{1}$$

In which the mass presented by M_s, K_s and C_s are the stiffness and damping values, $\ddot{u}\dot{u}$ and u are the acceleraion, velocity and displacement. This is presented for a nodal point of the finite element concept with the respect of time (*t*). On the other hand of the equation, F_p and F_g are presented the extra force “hydrodynamic force” and force vectors. They can be calculated as:

$$F_p = QP \tag{2}$$

$$F_g = -M_S I \ddot{u}_g(t) \tag{3}$$

The unit influence vector is defined as I, $\ddot{u}_g$ is the acceleration of the seismic loading, P is the reservoir water pressure, Q is the transformation matrix. Q is calculated based on the shape function of the pressure field and nodal displacement.

3. Description of LUSAS

Among several well-established finite element software, LUSAS is the remarkable one has been recognized over the literature in solving all kinds of linear and non-linear engineering problems such as stress, pressure, velocity, thermal and others [28]. The main merit of the program is in its capacity to act as a modeler and solver. The modeler LUSAS is a complete version of where an interactive graphical user can provide comprehensive results for the simulation analysis [29]. Whereas, the solver phase is the potential of the finite element analysis procedure that comprehends the conducted LUSAS modeler phase.

4. Dam analyses using LUSAS

LUSAS has long been well-known for its capabilities concerning the modelling of concrete. When modelling using continuum elements total strain-based crack models (fixed, rotating, multi-orthogonal) is suitable for modelling the tensile behaviour of concrete, coupled with a variety of choices of post-peak behaviour. Similarly, interface elements may be used for discrete crack analyses when crack patterns are known a priori.

Interface elements can also be used for the modelling of material interfaces, for example, the interface between founding soil and rock with a structure, coupled with a suitable constitutive model (Mohr-Coulomb, Rankine, etc.) [30].

A finite element model for the analysis of dams must possess the capability to apply/calculate the initial (stress) conditions within the dam and at the dam-foundation interface. The ability of a program to simulate multiphase phenomena is becoming an ever more important consideration for analyses modelling all aspects of a dam’s performance. For example, the ambient temperature may cause shrinkage of the dam concrete leading to cracking. In such a scenario a heat flow analysis coupled to the structural response, would be required. Similarly, seepage of water through the structure and founding soil and/or rock could be simulated using a partially saturated flow analysis with corresponding water pressures coupled to the structural response [31].

5. Example Benchmark Test

The CIGB/ICOLD A2 benchmark problem was chosen as the concrete gravity dam model for the analysis [32]. Concrete dam failure may occur through sliding or overturning, and the assessment of the failure mode requires consideration of the vertical uplift pressure and the horizontal hydrostatic pressure.

5.1 Finite Elements Method Analysis Process

5.1.1 Geometry

Figure 2 reports the geometric properties of the dam example in which (height = 80 m), (Width = 60 m).

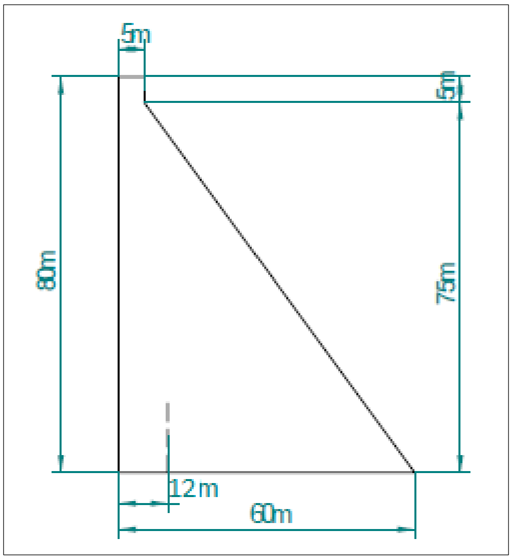
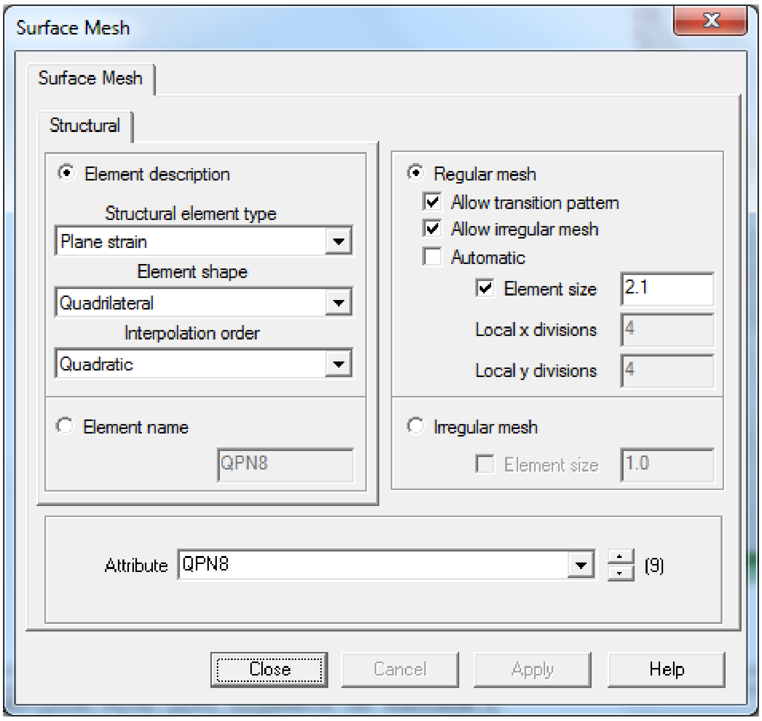


Figure 2. The dam geometry.

5.1.2 Meshing

For this study structural element type was used as plane strain, element shape is quadrilateral and interpolation order as quadratic and then element size was used to mesh the whole dam, and foundation 2.1 element size was used as shown in Figure 3.



● Element description

Structural element type: Plane strain

Element shape: Quadrilateral

Interpolation order: Quadratic

○ Element name: QPN8

● Regular mesh

☑ Allow transition pattern

☑ Allow irregular mesh

☐ Automatic

☑ Element size: 2.1

Local x divisions: 4

Local y divisions: 4

○ Irregular mesh

☐ Element size: 1.0

Attribute: QPN8 (9)

Figure 3. The surface meshing for the investigated dam.

5.1.3 Material

There are two types of material, concrete for the dam and rock for the foundation. Table 1 was presented the properties for each material.

Table 1: The concrete and rocks material properties used for the molded concrete dam.

Material parameters	Concrete	Rock
Young's Modulus (N/m^2)	24.0e9	41.0e9
Poisson's Ratio	0.15	0.1

Mass Density (kg/m^3)	2400	2200

Interface models are used to model the soil-structure interface and to reduce deformation before initiation of slipping behaviour, there is a need to define the relatively high dummy elastic properties. The modelling of the concrete-rock foundation interface is done using a Coulomb friction law, with the basic model input parameters being the cohesion, the friction tangent angle, and the tangent of the dilatancy angle. A gap criterion was also introduced, with the normal traction being considered zero the value of the tensile traction normal to the interface is above a specified critical value. Table 2 provides the properties of the material for the soil-structure interface.

Table 2: The soil-structure interface material properties.

Material parameters	**Coulomb Interface**
Dummy elastic stiffness	20e12 Nm^2
Cohesion	0.7e6 N/m^2
Friction angle	30^o
Dilatancy angle	10^o
Gap strength	0.35e6 N/m^2

5.1.3 Boundary Conditions

Another essential step of the FEM is setting the geometric boundary conditions. The modeling computations simplicity and efficiency for the materials belong to the foundation subjected with 120 m on the horizontal axis for both upstream and downstream. Whereas, vertically 80 m below the base foundation of the dam. Finally, the whole dam structure was fully fixed concerning the degree of freedom (see Figure 4).

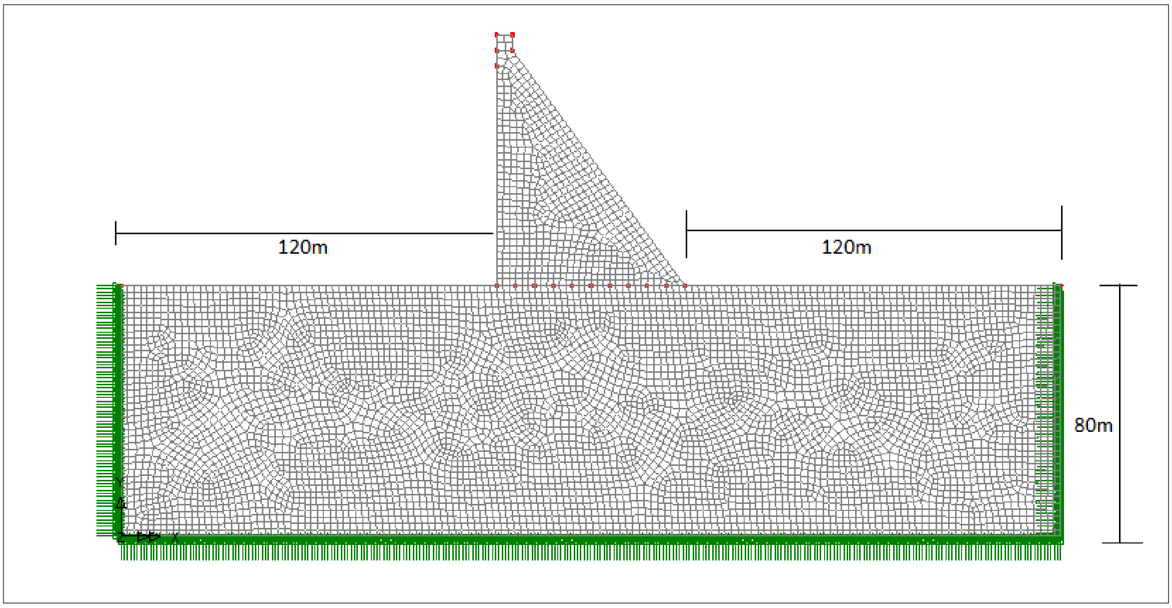


Figure 4. The assumption and location of the structural boundary conditions.

5.1.3 Loading Cases

Three load cases are considered in the analysis: case 1: no uplift, case 2: uplift with effective drain, and 3: uplift with ineffective drain (see Figure 5).

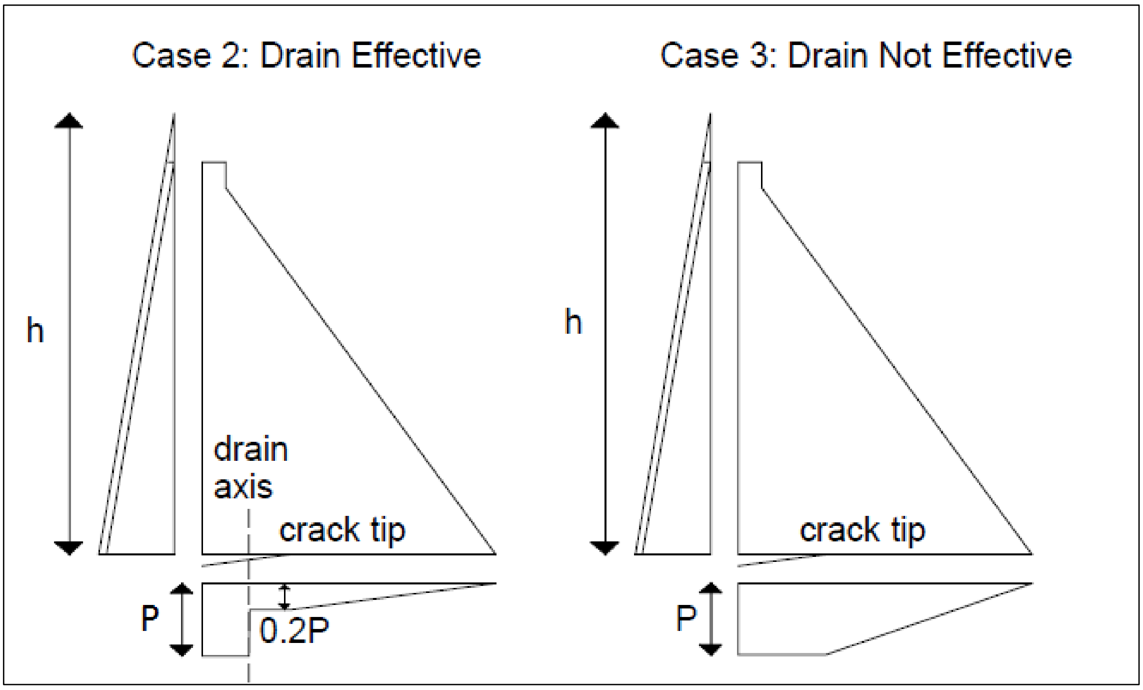


Figure 5. The diagram of the loading cases.

6. Modeling results and analysis

As per previous researchers, the Imminent Flood Failure Level (IFF) has been estimated for the case without uplift pressures and found to be about 100 m hydrostatic pressure and at this value, the slippage value of 27 m was recorded along with the dam-foundation interface from the dam heel, and additional 3m at the toe of the dam [33]. A fully effective drain is expected to have an IFF value of around 80 m. IFF value of around 80 m is also expected in cases where the uplift pressures are considered with an ineffective drain. The result of model analysis from LUSAS shows the relationship of crown displacement versus water level as in Figures 6, 7, 8 for three cases.

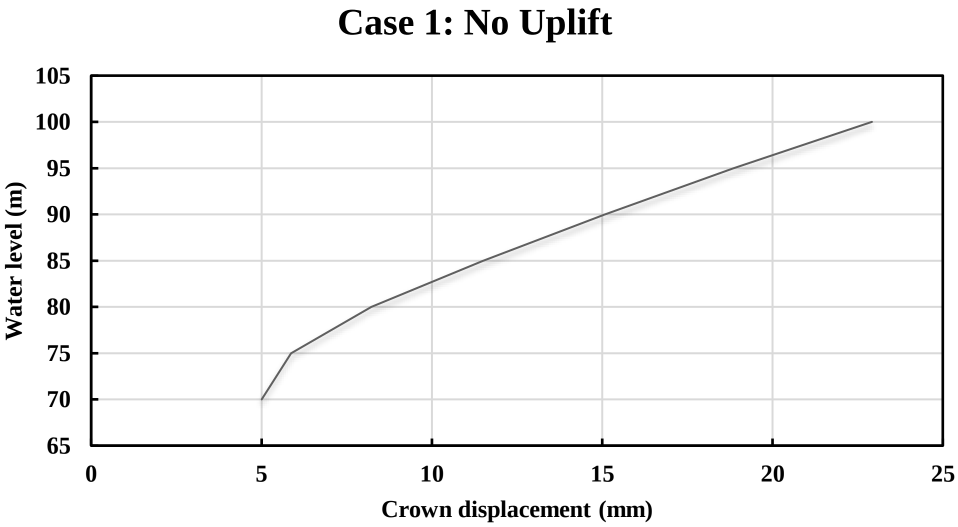


Figure 6. Case 1: No uplift: The crown displacement versus the water level.

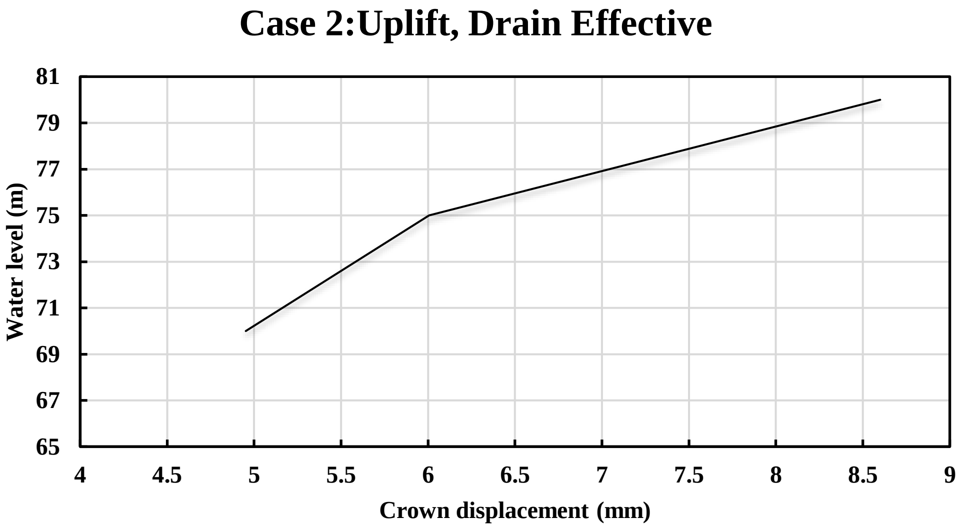


Figure 7. Case 2: Uplift, Drain Effective: The crown displacement versus the water level.

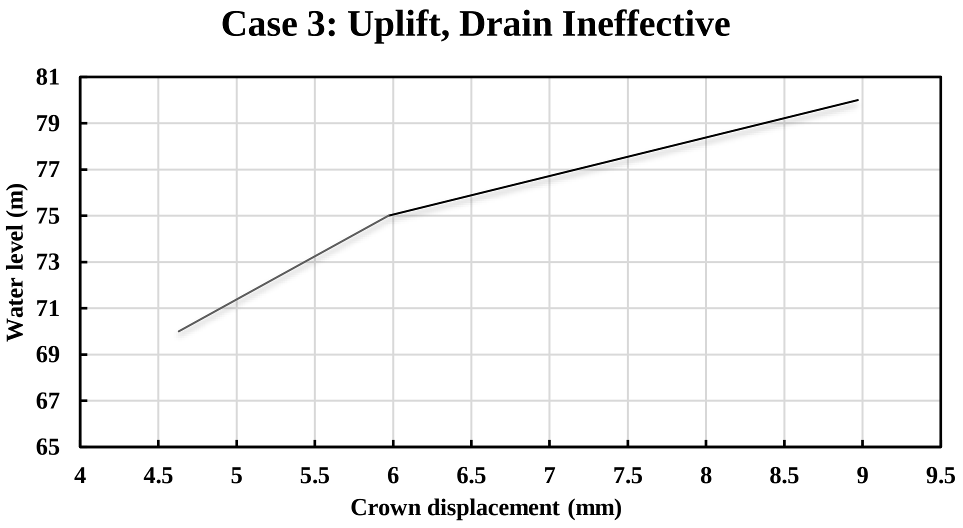


Figure 8. Case 3: Uplift, Drain Ineffective: The crown displacement versus the water level.

Figure 9 shows the maximum deformation in structure- foundation at load case 1 at 100 m water level. Whereas, Figure 10 shows the displacement in structure- foundation at load case 1 at 80 m water level. The current research was primarily established on the inspection of the uplift pressure with different cases and the investigation of the crown displacement versus the water level was reported. For future research, more insights can be further inspected that contribute to the dam practicality and sustainability.

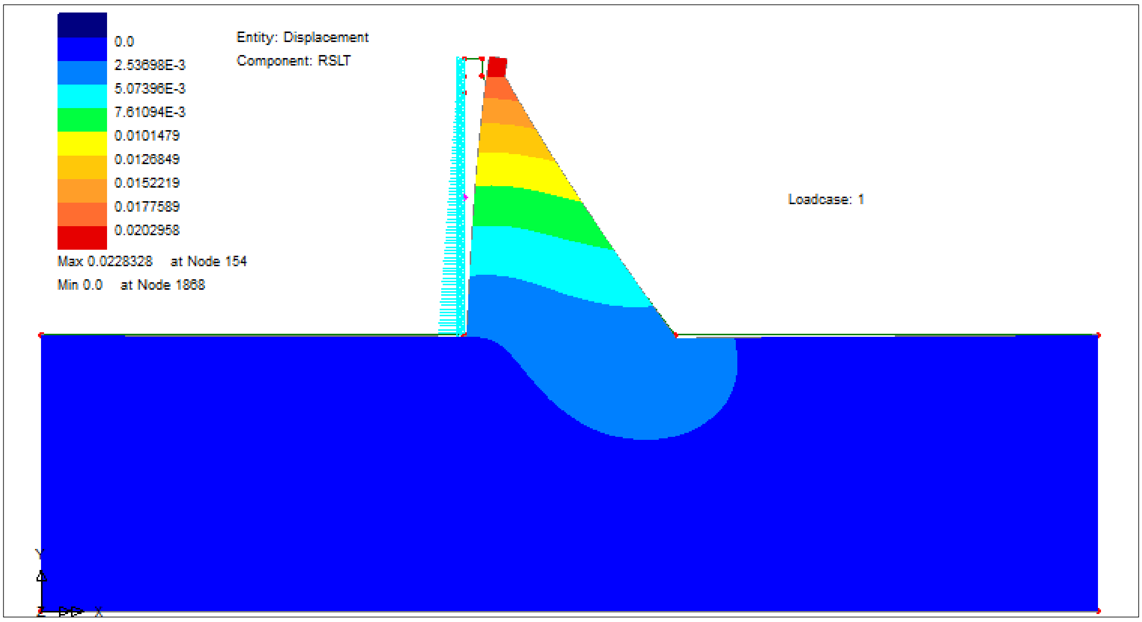


Figure 9. The maximum deformation in structure- foundation at load case 1 at 100 m water level.

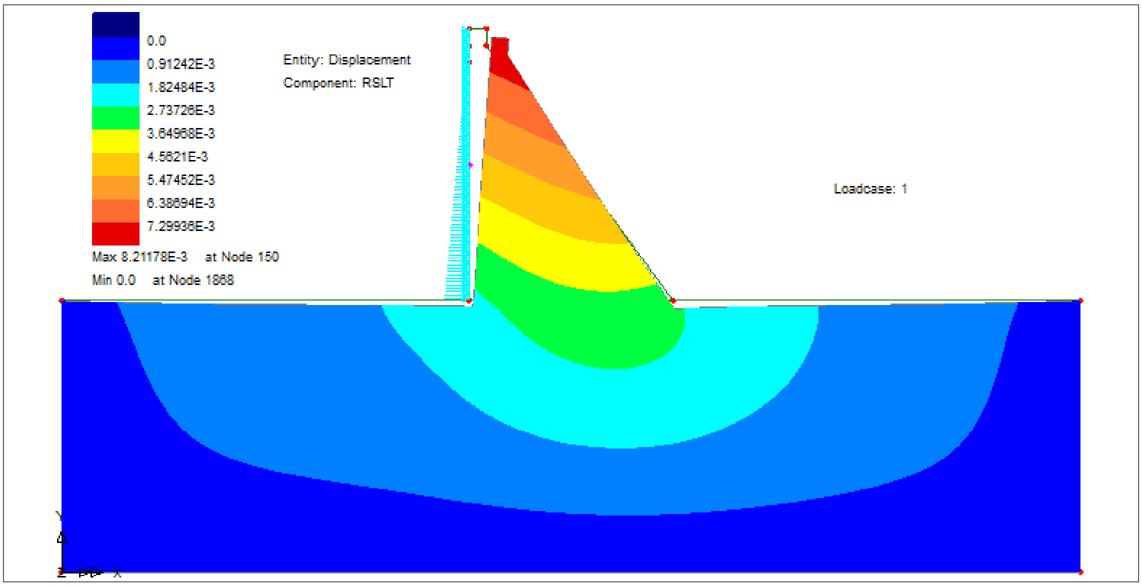


Figure 10. The displacement in structure- foundation at load case 1 at 80 m water level.

7. Conclusion

In this research, gravity dam failure was inspected based on the possibility of overturning or sliding. The feasibility of the finite element method was adopted for the analysis using the LUSAS modeler. Based on the attained modeling results, it was evidenced the capability of the finite element method to be applied to calculate the complex dam structure. The modeling procedure was established by segregating the structure into certain elements. It can be concluded that different types of load cases will cause different types of displacement. The Imminent Flood Failure (IFF) water levels for all the examined cases of the loading where no-uplift and non-effective drain, the results performed excellently as per the validations against the reported results by Linsbauer and Bhattacharjee. Nevertheless, it was observed the drain effectiveness could not perform sufficiently on the Imminent Flood Failure. The good comparison of the performance of LUSAS compared to other studies shows that, along with the comprehensive availability of material models and element types, LUSAS is ideally suited to the analysis of large dam problems.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] C. Marche and B. Robert, “Dam failure risk: Its definition and impact on safety assessment of dam structures,” *J. Decis. Syst.*, vol. 11, no. 3–4, pp. 513–534, 2002.

[2] Q. Chen, Y. H. Zou, M. Tang, and C. R. He, “Modelling the construction of a high embankment dam,” *KSCE J. Civ. Eng.*, vol. 18, no. 1, pp. 93–102, 2014.

[3] M. A. Hariri-Ardebili and S. M. Seyed-Kolbadi, “Seismic cracking and instability of concrete dams: Smeared crack approach,” *Eng. Fail. Anal.*, 2015.

[4] S. W. Alves and J. F. Hall, “Generation of spatially nonuniform ground motion for nonlinear analysis of a concrete arch dam,” *Earthq. Eng. Struct. Dyn.*, vol. 35, no. 11, pp. 1339–1357, 2006.

[5] P. Bukenya, P. Moyo, H. Beushausen, and C. Oosthuizen, “Health monitoring of concrete dams: A literature review,” *J. Civ. Struct. Heal. Monit.*, vol. 4, no. 4, pp. 235–244, 2014.

[6] W. E. Daniell and C. A. Taylor, “Effective ambient vibration testing for validating numerical models of concrete dams,” *Earthq. Eng. Struct. Dyn.*, 1999.

[7] C. H. Loh and T. S. Wu, “Identification of Fei-Tsui arch dam from both ambient and seismic response data,” *Soil Dyn. Earthq. Eng.*, 1996.

[8] G. R. Darbre, C. A. M. De Smet, and C. Kraemer, “Natural frequencies measured from ambient vibration response of the arch dam of Mauvoisin,” *Earthq. Eng. Struct. Dyn.*, 2000.

[9] G. R. Darbre and J. Proulx, “Continuos ambient-vibration monitoring of the arch dam of Mauvoisin,” *Earthq. Eng. Struct. Dyn.*, 2002.

[10] M. R. Mivehchi, M. T. Ahmadi, and A. Hajmomeni, “Effective techniques for arch dam Ambient Vibration Test: application on two Iranian dams,” *J. Seismol. Earthq. Eng.*, vol. 5, no. 2, pp. 23–34, 2003.

[11] S. W. Alves and J. F. Hall, “System identification of a concrete arch dam and calibration of its finite element model,” *Earthq. Eng. Struct. Dyn.*, 2006.

[12] R. Fedele, G. Maier, and B. Miller, “Health assessment of concrete dams by overall inverse analyses and neural networks,” *Int. J. Fract.*, 2006.

[13] C. Shao, C. Gu, Z. Meng, and Y. Hu, “Integrating the finite element method with a data-driven approach for dam displacement prediction,” *Adv. Civ. Eng.*, vol. 2020, 2020.

[14] A. Habib, A. A. L. Houri, M. Habib, A. Elzokra, and U. Yildirim, “Structural Performance and Finite Element Modeling of Roller Compacted Concrete Dams: A Review,” *Lat. Am. J. Solids Struct.*, vol. 18, 2021.

[15] R. Ardito and G. Cocchetti, “Statistical approach to damage diagnosis of concrete dams by radar monitoring: Formulation and a pseudo-experimental test,” *Eng. Struct.*, 2006.

[16] R. Ardito, G. Maier, and G. Massalongo, “Diagnostic analysis of concrete dams based on seasonal hydrostatic loading,” *Eng. Struct.*, 2008.

[17] A. De Sortis and P. Paoliani, “Statistical analysis and structural identification in concrete dam monitoring,” *Eng. Struct.*, 2007.

[18] B. S. Hussein and S. A. Jalil, “Hydraulic Performance for Combined Weir-Gate Structure,” *Tikrit J. Eng. Sci.*, vol. 27, no. 1, 2020.

[19] B. A. Mahmood and K. I. Mohammad, “Finite Element Analysis for RC Deep Beams under an Eccentric Load,” *Tikrit J. Eng. Sci.*, vol. 26, no. 1, pp. 41–50, 2019.

[20] A. El Gayar, “The evolution of modern embankment dam design and construction,” *Evolution (N. Y).*, vol. 9, no. 14, pp. 10–21, 2020.

[21] M. Papadrakakis, V. Papadopoulos, N. D. Lagaros, J. Oliver, A. E. Huespe, and P. Sánchez, “Vulnerability analysis of large concrete dams using the continuum strong discontinuity approach and neural networks,” *Struct. Saf.*, vol. 30, no. 3, pp. 217–235, 2008.

[22] M. J. Turner, R. W. Clough, H. C. Martin, and L. J. Topp, “Stiffness and deflection analysis of complex structures,” *J. Aeronaut. Sci.*, vol. 23, no. 9, pp. 805–823, 1956.

[23] B. Li, J. Yang, and D. Hu, “Dam monitoring data analysis methods: A literature review,” *Struct. Control Heal. Monit.*, vol. 27, no. 3, p. e2501, 2020.

[24] K. J. Panicker, P. Nagarajan, and S. G. Thampi, “Critical Review on Stress-Sensitivity and Other Behavioral Aspects of Arch Dams,” *Adv. Civ. Eng.*, pp. 551–566, 2021.

[25] B. Al-Zubaidy, N. S. Radhi, and Z. S. Al-Khafaji, “Study the effect of thermal impact on the modelling of (titanium-titania) functionally graded materials by using finite element analysis,” *Int. J. Mech. Eng. Technol.*, no. 1, 2019.

[26] S. Zhang, G. Wang, and X. Yu, “Seismic cracking analysis of concrete gravity dams with initial cracks using the extended finite element method,” *Eng. Struct.*, vol. 56, pp. 528–543, 2013.

[27] K. Ghaedi, F. Hejazi, Z. Ibrahim, and P. Khanzaei, “Flexible foundation effect on seismic analysis of Roller Compacted Concrete (RCC) dams using finite element method,” *KSCE J. Civ. Eng.*, vol. 22, no. 4, pp. 1275–1287, 2018.

[28] I. Rozaina, K. M. Hilfi, and M. N. N. Insyirah, “Seismic analysis of concrete dam by using finite element Method,” in *MATEC Web of Conferences*, 2017, vol. 103, p. 2024.

[29] G. C. SianG, “The Tembat Hydropower Dam Project-Determination of coefficient of thermal expansion (CTE) of 20MPa mass concrete using granite aggregate,” *Concr. Mod. Age Dev. Mater. Process.*, p. 141, 2017.

[30] M. Paggi and P. Wriggers, “A nonlocal cohesive zone model for finite thickness interfaces–Part II: FE implementation and application to polycrystalline materials,” *Comput. Mater. Sci.*, vol. 50, no. 5, pp. 1634–1643, 2011.

[31] A. M. Raheem, “Total Head Evaluation using Exact and Finite Element Solutions of Laplace Equation for Seepage of Water under Sheet Pile,” *Tikrit J. Eng. Sci.*, vol. 25, no. 3, pp. 40–46, 2018.

[32] A. Desideri, E. Fontanella, and L. Pagano, “Pore water pressure distribution for use in stability analyses of earth dams,” in *Landslide Science and Practice,* Springer, 2013, pp. 149–153.

[33] L. Zhang, M. Peng, D. Chang, and Y. Xu, *Dam Failure Mechanisms and Risk Assessment*. 2015.