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Parametric Study of the Modal Behavior of Concrete Gravity Dam by Using the Finite Element Method

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Abstract

Considering the period of the first mode of dams is an essential part of its seismic behavior analysis. Therefore, it is crucial to calculate the natural frequencies. This paper aim is simulating and analysis of the finite element (FE) model of the Koyna concrete gravity as a case study. In order to investigate the suitable mesh size to achieve the grid independency, the element size is considered as a variable parameter and its optimized value is determined by using the Response Surface Optimization (RSO) method. In the independent grid, to controlling mesh quality, the Error Contour is utilized, which indicates fast variations of the energy in the adjacent elements and can recognize parts of the model that has a high error in calculating responses. The modal response of the dam with a rigid and flexible foundation with and without mass is appraised. The results indicated that modal frequencies in the condition of with and without Pre-stress are different in all cases. Moreover, the frequencies of the first four modes by increasing the mass and decreasing the stiffness of foundation, frequencies in the case without initial condition (without Pre-stress) have a slight increase and in the case with initial condition (Pre-stress) have considerable decrease.

Keywords: Modal Analysis; Concrete Gravity Dam; Grid Independence; Response Surface Optimization (RSO); Error Contour; Pre-stress.

1. Introduction

In the design of structures based on the response spectrum, the period of the first mode of the structure (structural period) is used to define spectrum acceleration (S_a). In regular structures, the behavior of the structure is largely dependent on the first mode period. Therefore, calculating the natural frequency of dams is an essential part of its seismic behavior analysis. Besides, the upshot of the frequency analysis can be used for damping calculation and the response spectrum analysis to evaluate the seismic behavior of the dam. Modal analysis is the process of determining the intrinsic dynamic specifications of the system in the form of natural frequencies, damping coefficients, and the shape of modes and applying them to create a mathematical model of the dynamic behavior of the system. Modal analysis is focused on the principle that the vibration response of the linear dynamic system is a collection of simple coordinate actions that are in vibration modes. This concept is similar to using a Fourier combination of sin and cos waves to show a complex wave. Vibration mode shape is related to system dynamic which is determined by physical specifications such as mass, stiffness, damping, and their distribution method. Each mode is described based on the modal parameters of the same modes, including the natural frequency, the modal damping coefficient, and the displacement pattern in that mode which is called mode shape. Mode shape may be real or imaginary and each mode corresponds to a natural frequency. The

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contribution amount of each natural mode in the vibration of the entire system depends on the specifications of the stimulation source and mode shape [1].

Chopra [2] observed that the response of the short-period vibration structure, such as the concrete dams subjected to seismic was largely influenced by the fundamental mode of vibration, and in his analyzes, Chopra also concluded that the vertical components of the ground acceleration had little influence on the structure response. Chopra and Chakrabarti [3] introduced a general procedure for the analysis of the response of concrete dams, including the dynamic effects of water and the flexible foundation to the horizontal and vertical components of soil movement. Fenves and Chopra [4] developed a semi-analytical-numerical technique to analyze the earthquake response of concrete gravity dams using two special cases (a) full reservoir dam supported by a rigid foundation; and (b) an empty reservoir dam supported by a flexible foundation, concluding that in the first case, the dam-reservoir effect and the bottom of the lake are relevant to the dam response, whereas in the second case the dam response is only related to the foundation and the dam. Domanguez et al. [5] studied the effect of the reservoir-foundation interaction wherein they proposed a contour integral technique to investigate the response of the dam reservoir-sediment-foundation systems subject to soil displacements. Arabshahi and Lofti [6] conducted a study on the mechanisms of natural vibration due to damage on the interface at the bottom of the dam, starting from a plasticity-based formulation using the local stresses of the element on the interface to model the sliding as well as the partial cracks along the foundation.

Shariatmadar and Mirhaj [7] evaluated the hydrodynamic pressures induced due to seismic forces and Fluid-Structure Interaction (FSI) using the ANSYS program. The results showed that the accurate modeling of dam-reservoir-foundation and their interaction considerably affects the modal periods, mode shapes and modal hydrodynamic pressure distribution. Pasbani Khiavi et al. [8] assumed that the boundary and the reservoir interface are vertical, the reservoir base is rigid and horizontal, and the fluid in the reservoir is not incompressible and viscous. The relevant boundary conditions (BCs) and equations have been applied according to the finite element method (FEM) with considering horizontal and vertical earthquake components. Sevim et al. [9] determined the dynamic characteristics of a prototype arch-reservoir-foundation dam system using the modal analysis method including local vibration tests in the arc dam model identifying its natural frequencies and modes of vibration. Khosravi et al. [10], Khosravi and Heydari [11] considered geometry variables to analyze the gravity dams, which is two-dimensional finite element (FE) model included a dam, reservoir, and foundation, by using ANSYS APDL. The results showed that considering the dam-reservoir-foundation interaction has an important role in safely designing a gravity dam.

Mahdizadeh and Ghanbari [12] concerned a new formulation for the natural frequency of gravity dams utilizing the analytical method. In this method, shear wave velocity and height of the dam are two parameters which are used for obtaining natural frequency and show that there is no significant difference in the dam with various heights. Aghajanzadeh and Ghaemian [13] investigated the seismic performance of a concrete gravity dam to evaluate the effect of the foundation on the nonlinear response using the FEM. They used an elasto-plastic formulation to model the foundation. Mohr-Coulomb model and smeared crack model were utilized for the yield of the foundation and dam body, respectively. The results show that cracks form at the crest and the hill of the dam. Pasbani Khiavi [14] investigated the reservoir bed characteristics effect on reducing the induced pressure in the reservoir. The results confirmed a high dependence of responses to the reservoir bottom absorption. Additionally, Pasbani Khiavi [15] investigated the influence of the concrete stiffness on the seismic responses of concrete gravity dams by the Monte Carlo simulation. According to the results, the optimized value of the concrete young modulus to access the confident response of the structure was achieved, which was important concerning the economic aspects. Seleemah et al. [16] used the ANSYS software to analyze the dynamic response of the dam reservoir-foundation system to showing that the results of stresses and displacements are significantly affected when it has flexibility in the foundation. Taylan, and Aydın [17] considered the Darideresi-II dam and used ANSYS Workbench to investigate the responses under different earthquake accelerations. Silveira and Pedroso [18] evaluated the influence of the foundation and reservoir on the dynamic response of concrete gravity dams as a function of their parameters in terms of natural frequencies and mode of vibration. The dam reservoir-foundation interaction will be investigated through the modal analysis by the FEM via the ANSYS APDL software.

In this paper, the ANSYS standard version is used for modeling and analysis. It should be noted that the standard version of this software has the ability to apply various boundary conditions and the effects of interaction between the dam, reservoir and foundation. To apply the interaction effect, the FSI command contained in this software has been used. ANSYS is a software program based on the FEM and is used to give more accurate results for complicated geometries. In this method, the geometry is divided into small parts and the BCs are applied. Finally, the results are obtained for each node or element [17]. During the process of this study, ANSYS Workbench software is used [19]. The main innovations of this paper are the Response Surface Optimization (RSO) method utilization to investigate the influence of grid dimension on responses and the Error Contour method utilization to verify the appropriate dimension for the minimum computational error on achieving the grid independence.

2. Case Study

In this study for simulation and analysis a non-overflow monolith of the Koyna concrete gravity dam located in India [20] with 103 m height, two-dimensional, and the plane stress behavior as illustrated in Figure 1 has been considered as a case study to evaluate the modal performance of the Koyna dam under modal analysis. Due to the devastating earthquake experience, this dam has been more studied. Moreover, the properties of the allocated material for the concrete dam, the foundation, and the reservoir based on experience and background of studies are listed in Table 1 [21-28].

In the ANSYS Workbench, several analysis systems are linked together to analyze the model. In the Structural Analysis part, the material specifications are assigned and BCs are specified in the dam model. Also in this section, the water's has given force to the dam, which is defined as hydrostatic pressure, has exerted to the dam. Then, RSO from the Design Exploration linked with the Structural Analysis part to the parametric study of the element size to approach the grid independence. Finally, Modal Analysis linked to the Structural Analysis part to determine the modes of the structure. If the model statically analyzed and induced responses are applied as an initial condition (IC) for new analysis, this type of analysis called Pre-stress condition and if there is not any IC, the analysis is considered as without Pre-stress. For modeling and analysis, the Koyna dam with the two conditions of the rigid and flexible foundation with and without mass are simulated and modal analyzed. Then free vibration frequencies with and without Pre-stress are extracted and frequency responses of modes are compared and assessed in these six specimens (chart available in Figure 9).

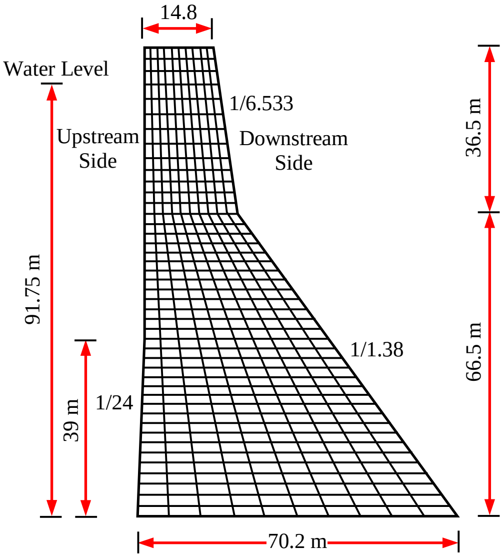


Figure 1. The geometry and FE model of the Koyna dam [29]

Table 1. Summary of the material properties

Material	Property	Value
Dam body (Concrete)	Density (Kg/m^3)	2643
	Young's modulus (MPa)	31027
	Poisson's ratio	0.2
	Damping	0.05
	Compressive initial yield stress (MPa)	12.6
	Compressive ultimate stress (MPa)	27.11
Foundation (Bedrock)	Density (Kg/m^3)	2701
	Young's modulus (MPa)	16860
	Poisson's ratio	0.18
Reservoir (Water)	Density (Kg/m^3)	1000
	Bulk modulus (GPa)	2.2
	Poisson's ratio	0

3. Grid Independence

In this paper, the FEM is used, which is the science of discretization of the continuous system into smaller and separate elements and analyzing discrete elements. If the type and dimension of the elements are suitably appointed, the simulated model has exact results and close behavior to the behavior of the real model. Therefore, there is less error in the calculations [30]. Though the fine mesh or element size reduces the error and augment the accuracy of the response, but should insomuch be enough shrinking that by changing the element size, the response changes in the model should have negligible. If changing the grid dimension does not affect the model responses, and the responses are independent of the grid dimension, namely reached the response stability. This concept of grid discretization to attain the convergence and stability of the response from the mesh or element size is called grid independence. To discretization the FE model, the 8-node square element has been used and the mesh independent studied. For this cause, the element size in the RSO parametric analysis method between 0.1 to 2 m has been chosen as input variable parameter and the resultant displacement of the crest, Pre-stress frequency of the first mode, and the number of elements and nodes of dam model were considered as the output variables.

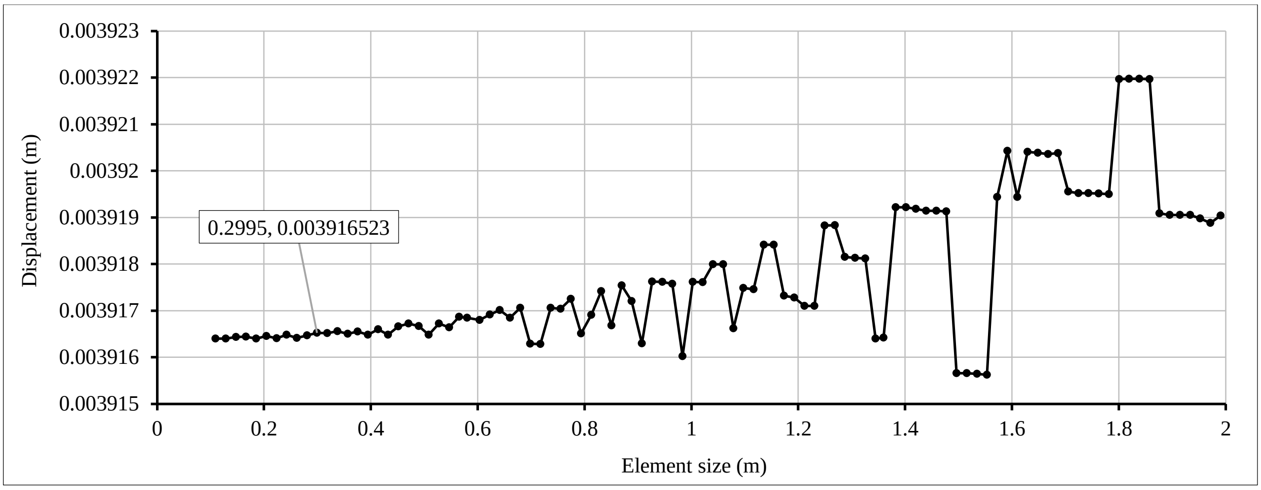


Figure 2. The curve of the element size variation effect on the dam crest displacement

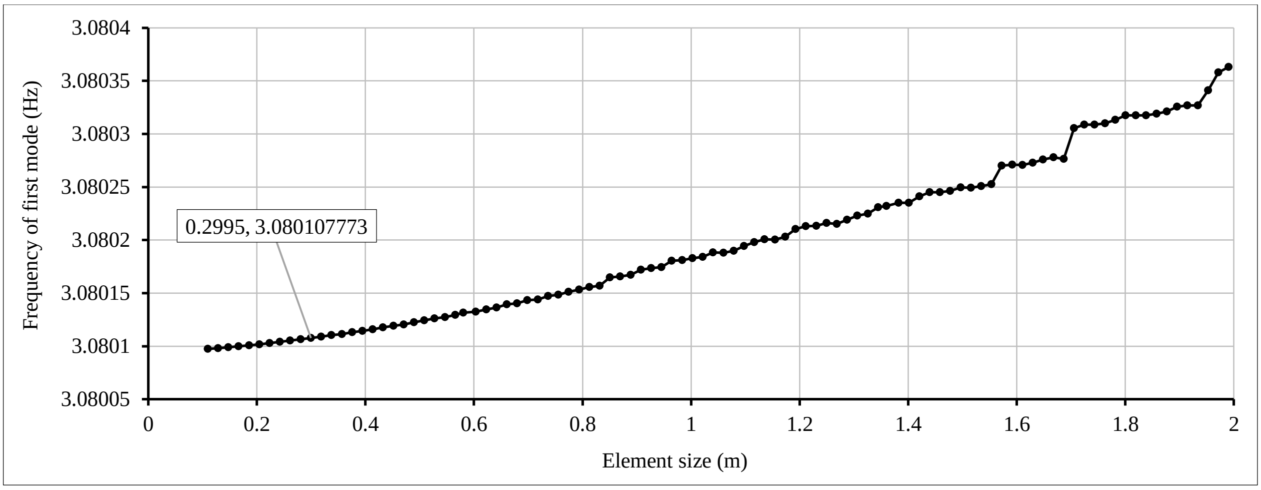


Figure 3. The curve of the element size variation effect on the frequency of the first mode

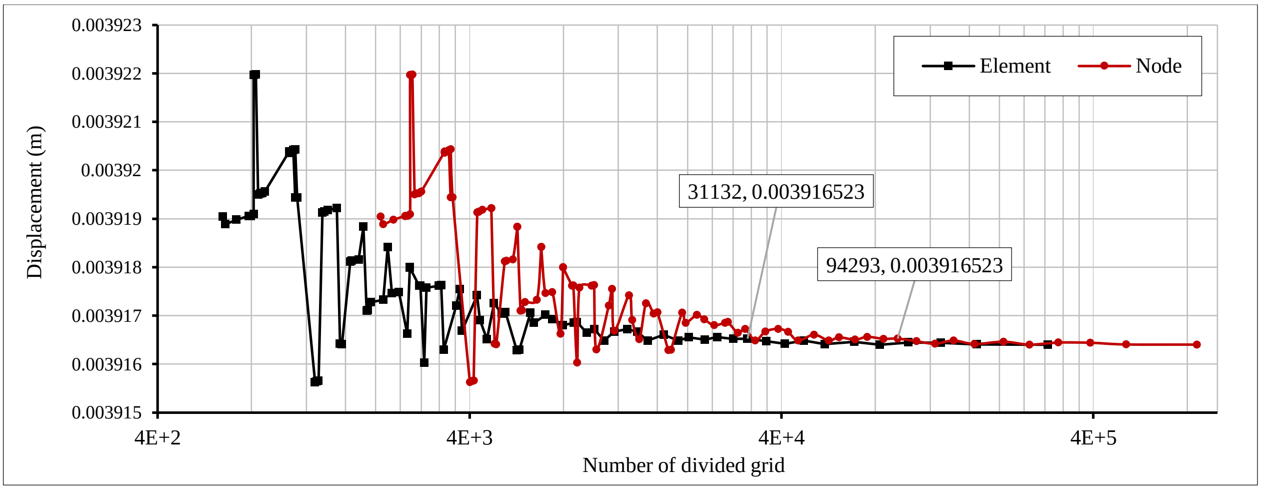


Figure 4. The curve of the element size and node number variation effect on the dam crest displacement

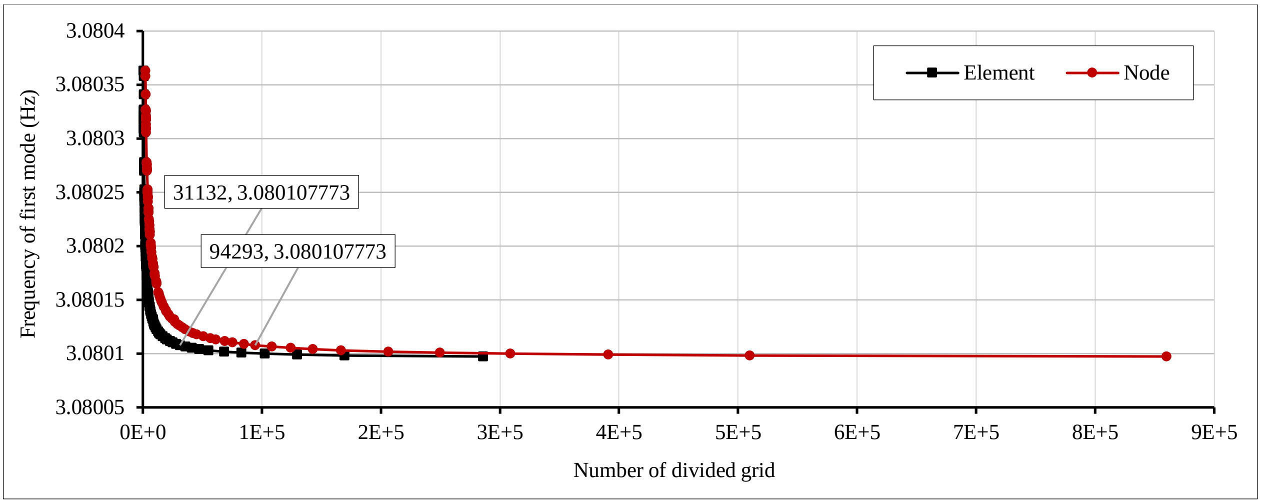


Figure 5. The curve of the element size and node number variation effect on the frequency of the first mode

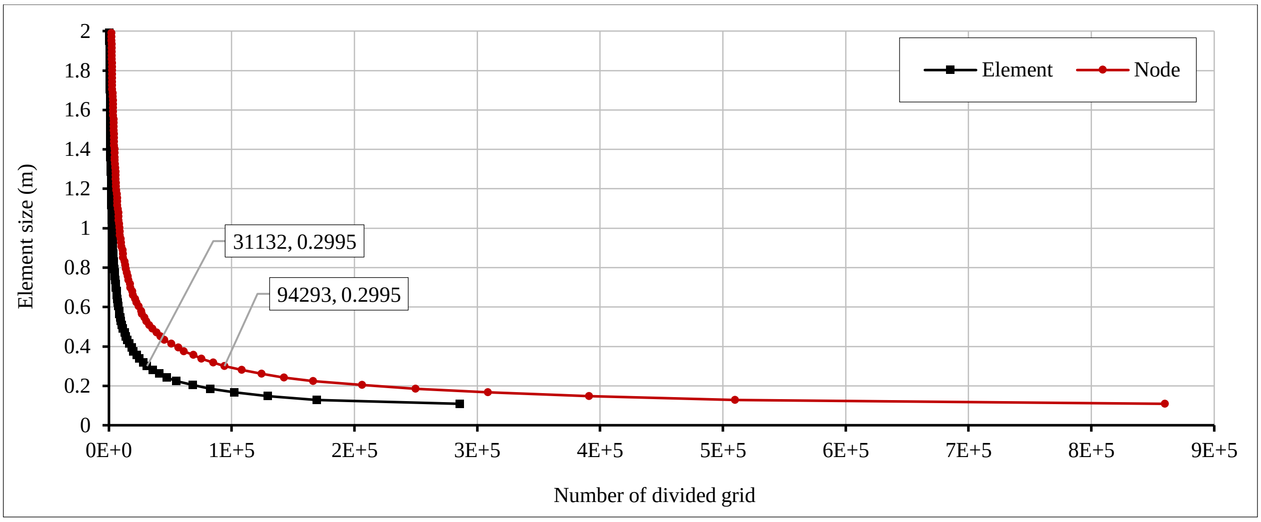
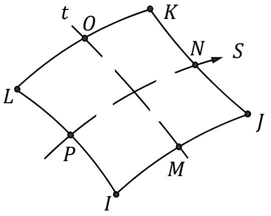


Figure 6. The curve of the element size variation effect on the number of element and node

Figures 2 to 6 shows the effect of the element size and number on the responses for the achievement of grid independence. Figure 2 and 3, indicates the effect of the element size between 0.1 m to 2 m on the consequences of the displacement of dam crest and the frequency of the first mode, respectively, which by decreasing the size of an element, displacement and frequency achieved convergence. Figure 4 and 5, illustrates the effect of the element size and node number gave out from the grid discretization on the dam crest displacement and frequency of the first mode. It is obvious from the figures by decreasing the element size, the number of elements and nodes will be increased and displacement reaches convergence. Figure 6 presents the effect of the element size variation upon the number of elements and nodes to attain the grid discretization, which by decreasing the element size, the number of elements and nodes will be increased. When the element size becomes excessively small, the number of elements and nodes suddenly increases and reaches to diverge and the calculation time will be time-consuming.

By surveying Figure 2 to 5, it can be observed that with the certain element size in which the displacement curve and the frequency of the first mode tend to converge. The number of elements and nodes in Figure 6 get into the divergence threshold. As the dimensions of the grid diminish, the model's stiffness decreases and becomes closer to the actual model. Because the frequency has a direct relation with the stiffness, in Figure 3 and 5, it is obvious that the element refinement cause increases the element and node number and reduces the first mode frequency (in the Pre-stress condition) and stiffness. Furthermore, by increasing the number of element and node, the dimension of the matrix equation become larger and solve will be time-consuming. Considering the concept of grid independence, the appropriate element size can be estimated as 0.3 m in which the responses have reached to the convergence and the discretizing of the grid is not required smaller. The specification of the element type and the final discretization is briefly listed in Table 2.

Table 2. Summary specification of the element type used in the discretization

Element Type	PLANE 183 2D Quad-8 Node	
No. of Elements	31132	
No. of Nodes	94293	
Element Size (m)	0.3	

In the following, by considering the characteristics given in Table 2, the analysis is carried out and the mesh quality for 0.3 m element size is evaluated. In Figure 7, the distribution of the quality of the elements with three separate criteria is assessed, which has a value between 0 and 1. These three criteria are [19]:

- Skewness Quality: if closer to 0, it has a higher mesh quality and lower elongation of the elements.
- Element Quality: if closer to 1, it has a higher mesh quality and square elements.
- Orthogonal Quality: if closer to 1, it has a higher quality with elements of about 90 degrees.

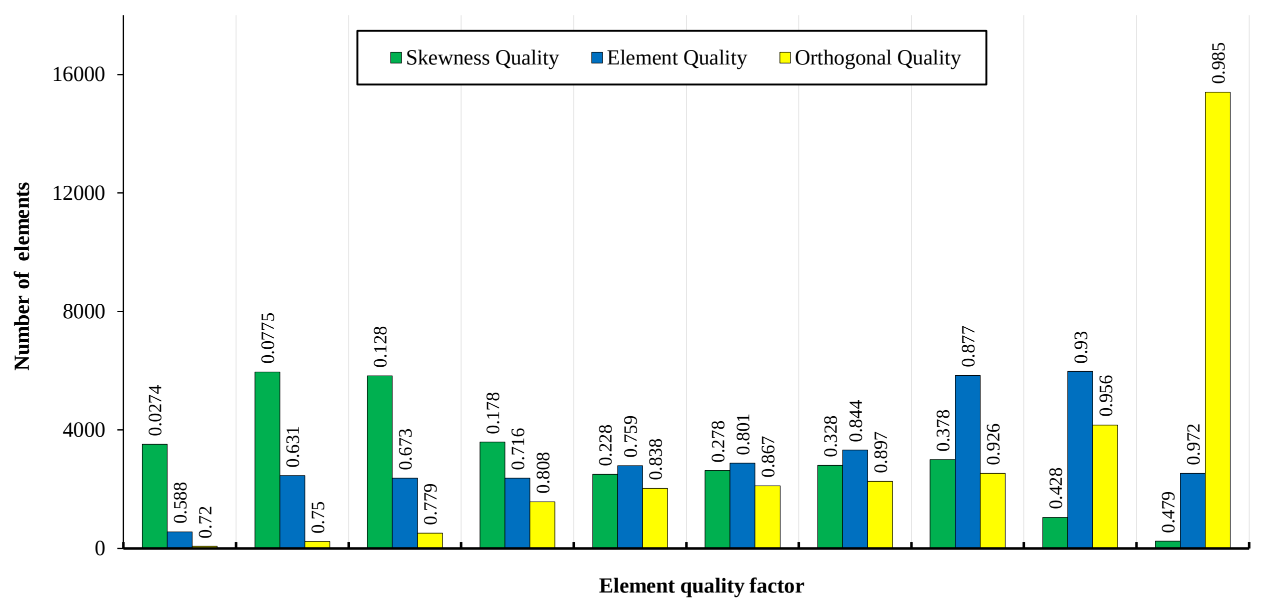


Figure 7. Chart of the mesh generating quality of the dam system with the rigid foundation

Figure 7 presents the distribution of the number of elements in terms of the three criteria of the mesh quality that the coefficient of all three criteria were close to the appropriate value (e.g. Orthogonal Quality has 15400 elements with 0.985 coefficients). With remarking to the range of variations in the number of elements and coefficients in any type of criterion, it can be figured out that almost all square elements have less elongation and close to 90 degrees, which indicates the quality and composition of the appropriate discretization for the FE model.

4. Error Contour

Utilization of the Error Contour is a method for controlling the mesh quality of the FE [19], which indicates the rapid variation of the energy in the adjacent elements. The Error Contour can identify areas of the model that have high error rates in the stresses calculating and at which parts need to make the element smaller to obtain more accurate responses. Therefore, improving the mesh quality cause reduces the energy difference in the adjacent elements. After surveying the grid independence, the discretization quality (mesh quality) of the case study model by using the Error Contour has been investigated (in Figure 8). The most critical area is in the heel of the dam, which its energy difference is not significant and indicates the suitability of the element size.

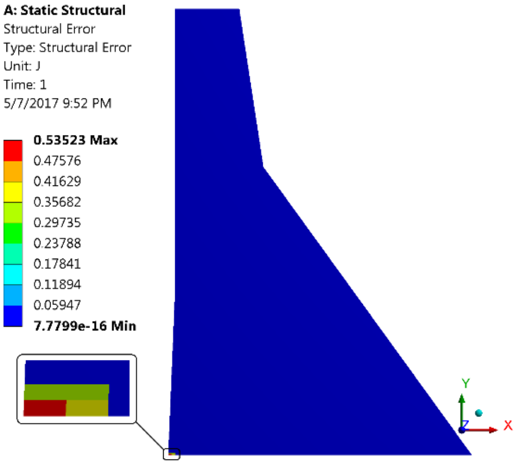


Figure 8. Error Contour for the static analysis of dam model

5. Frequency Analysis of the Model

Frequency or modal analysis is a method for determining vibration specifications of the structure. The structure without loading can vibrate at special frequencies. These frequencies are natural frequency and vibrations are free vibrations. The deformation of the structure in each frequency is named mode shape. If the structure is forced to vibrate at a particular frequency, it can vibrate at frequencies other than the natural frequency. This frequency is excitation frequency and the vibration is forced vibration. If the natural frequency is close to excitation frequency, the resonance phenomenon can occur. In other words, if the structure is being forced to vibrate at its natural frequency, resonance will occur and large amplitude vibrations will be observed. Therefore, modal analysis permits the designer to prevent severe vibrations or vibrates in special frequency [19]. Figure 9 shows a chart of the analysis process during this paper (responses signed with color and series).z

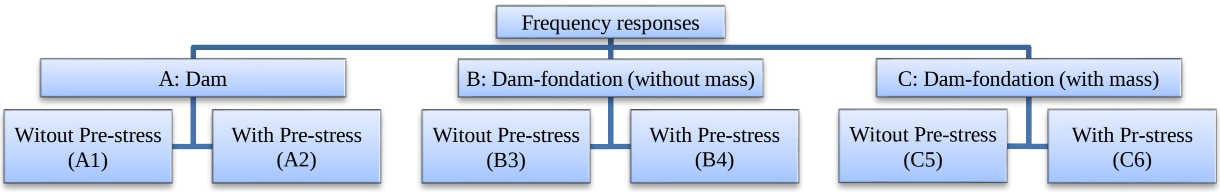


Figure 9. Chart of analysis process and specimens

5.1. Frequency Analysis of the Dam with a Rigid Foundation (Model A)

In this section, the dam system with a rigid foundation is considered to evaluate of the mesh independence and natural frequencies. Estimation of the natural frequencies of the dam was determined by considering the conditions of plane stress without interaction between the dam, reservoir, and foundation. The free vibration frequencies with and without the Pre-stress condition (A1 and A2) for the first four modes derived from the simulation of the dam system with the free vibrational frequencies of Huang [21] results were given in Table 3.

Table 3. Comparison the frequencies of the Model A with and without Pre-stress

Mode No.	Calculated free vibration (Hz)		Reference free vibration (Hz) [21]	%Error
	Without Pre-stress (A1)	With Pre-stress (A2)	With Pre-stress	
1	0	3.0801	3.08	-0.0032
2	0	8.2309	8.23	-0.0109
3	1E-05	10.825	10.82	-0.0462
4	6.1396	15.984	15.98	-0.0250

The frequency of vibrational modes has a significant difference in the two cases of frequency analysis. Also, the error rate obtained from comparing the simulated model with the reference model is very low, indicating the accuracy of the model. Figure 10 shows the mode shape for the first four modes of free vibration frequency responses of Model A2. Also, Figure 11 illustrated the cumulative percent of the mass contributions for each mode in the Model A2 upon the vertical, horizontal, and rotational direction around the perpendicular axis. If the superposition principle is used, it is possible to use the first six modes that provided 90% of the amount of mass participation.

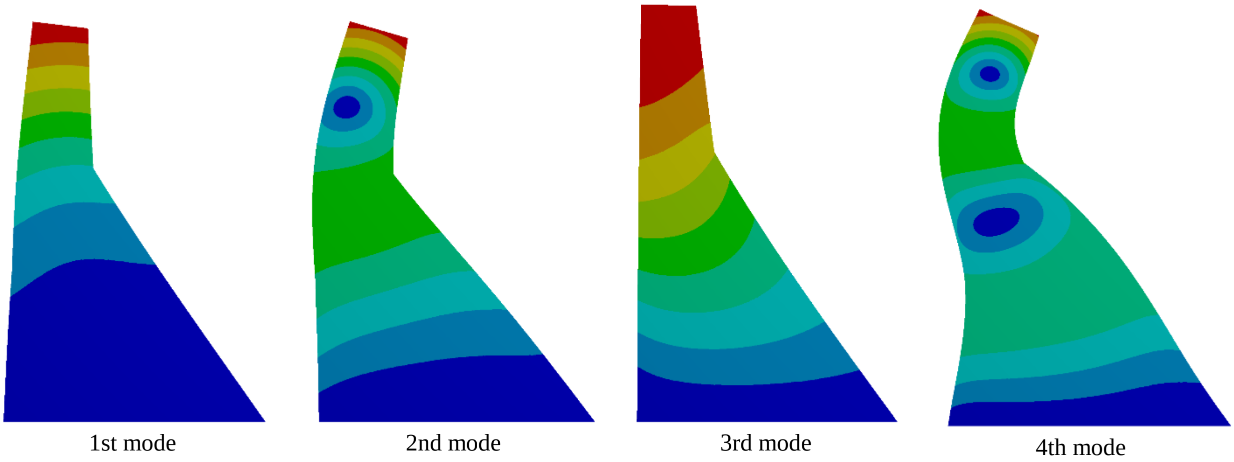


Figure 10. Mode shapes of the dam (Model A1) in the first four modes

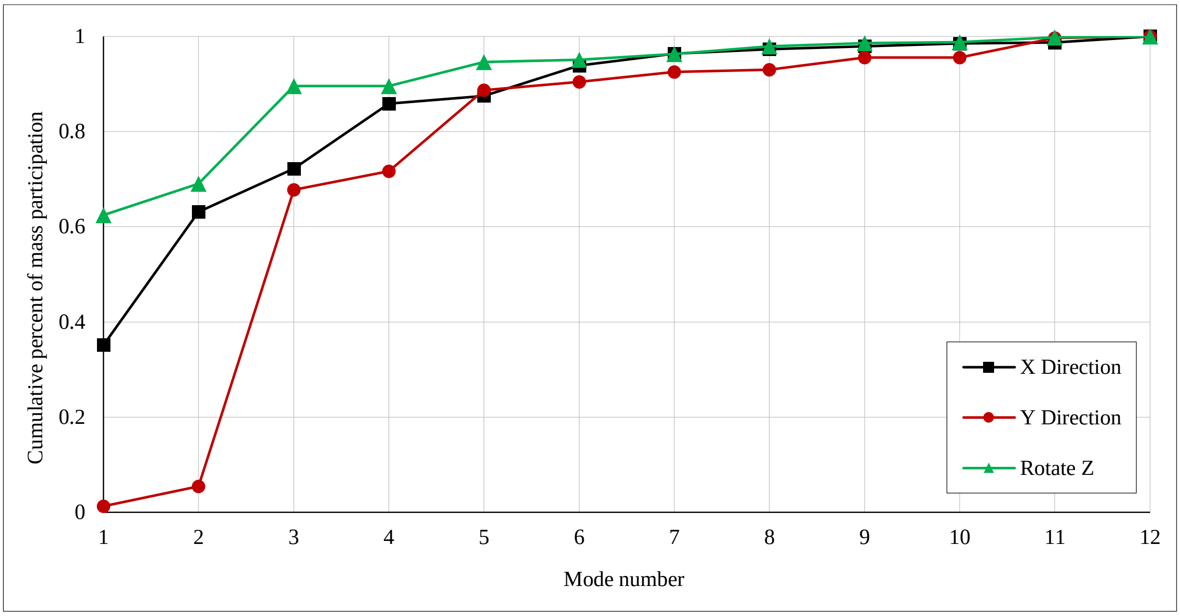


Figure 11. Cumulative percent of the mass participation in the each mode of Model A2

5.2. Frequency Analysis of the Dam with a Flexible Foundation without Mass (Model B)

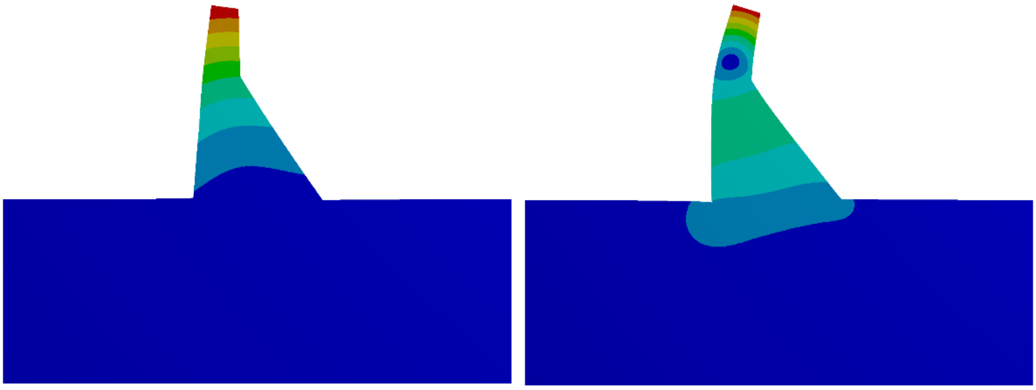
In this section, the dam system with an elastic foundation without mass (massless) simulated and natural frequencies are calculated. Obtained results of the natural frequency of free vibration for two cases of with and without Pre-stress (B3 and B4) presented in Table 4. The results show an increase of modal frequency in the Pre-stress condition relative to the without Pre-stress condition.

The comparison of Table 3 and Table 4 frequencies without Pre-stress has little increase and frequencies with Pre-stress decreases because of the decrease of foundation rigidity

Table 4. Free vibration frequencies of dam system with the elastic foundation without the mass in the first four modes

Mode No.	Calculated free vibration (Hz)	
	Without Pre-stress (B3)	With Pre-stress (B4)
1	6.93E-06	2.3916
2	8.30E-06	5.7819
3	1.98E-05	6.1909
4	6.1662	11.166

Figure 12 shows the mode shapes of the first four modes for free vibration of the model with the Pre-stress condition. Also, Figure 13 illustrated the cumulative percent of the mass contributions for each mode in the Model B5 upon the vertical, horizontal, and rotational directions. If the superposition principle is used, it is possible to use the first three modes that provided 90% of the amount of mass participation.



1st mode 2nd mode

3rd mode 4th mode

Figure 12. Mode shapes of Model B4 in the first four modes

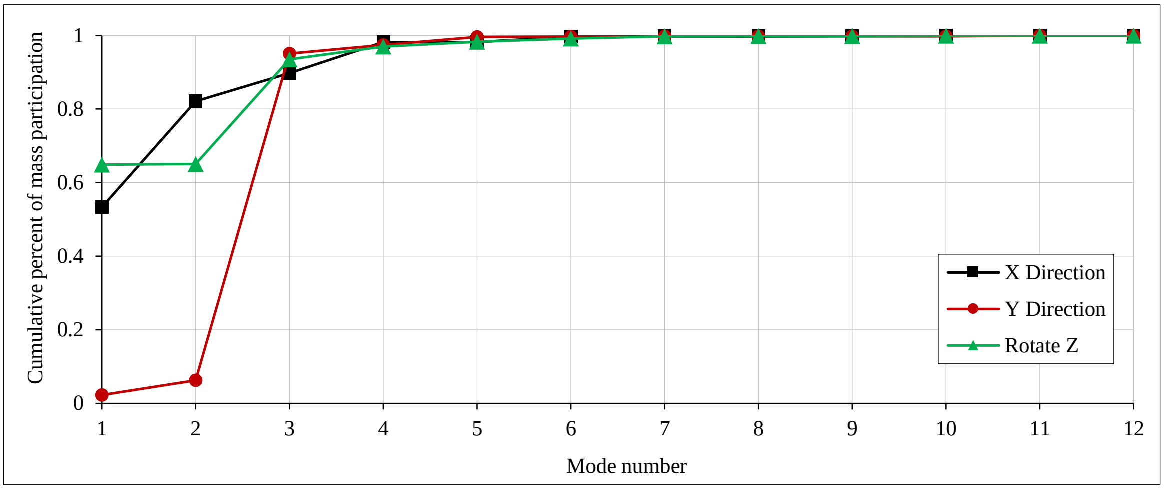


Figure 13. Cumulative percent of the mass participation in the each mode of Model B4

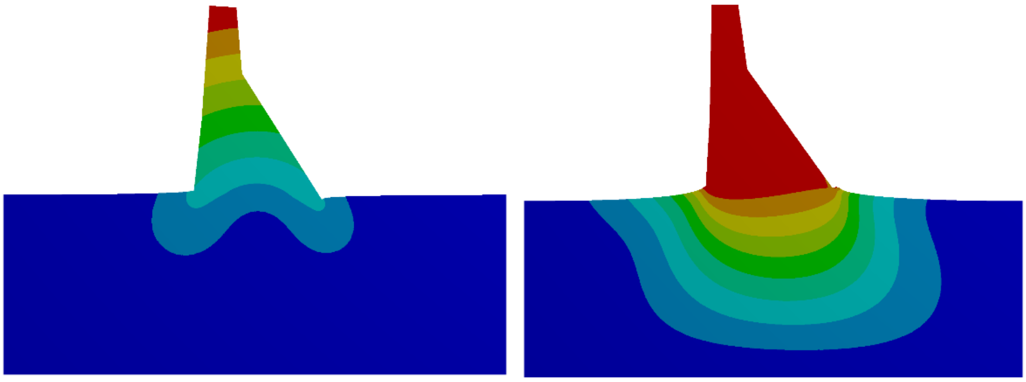
5.3. Frequency Analysis of the Dam with a Flexible Foundation with Mass (Model C)

In this section, the dam with a flexible foundation with mass analyzed and the natural frequencies are calculated. Obtained results of the natural frequencies for two cases of with and without Pre-stress (C5 and C6) presented in Table 5. Comparison of the results shows that the Pre-stress condition caused increasing the frequencies. Also, the comparison of obtained frequencies for two cases of the flexible foundation with and without mass in Table 4 and Table 5 discloses that the model without mass frequencies (C5) has rather than the model with mass (C6).

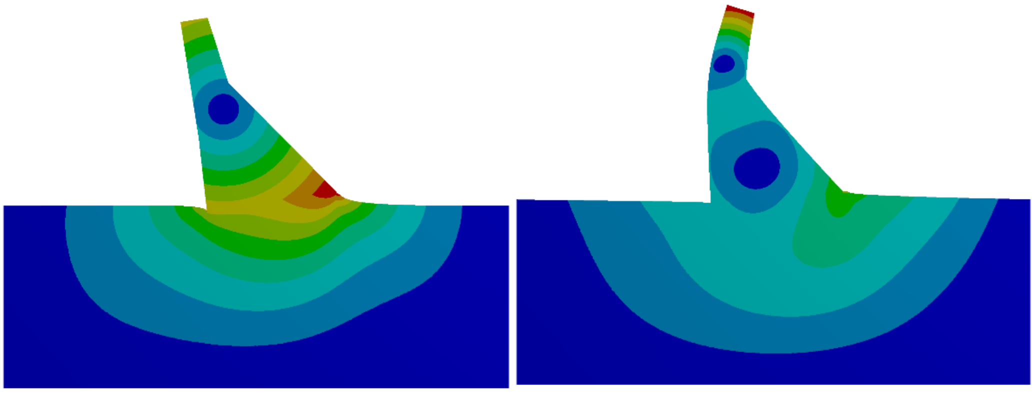
Table 5. Free vibration frequencies of the dam system with the elastic foundation with the mass in the first four modes

Mode No.	Calculated free vibration (Hz)	
	Without Pre-stress (C5)	**With Pre-stress (C6)**
1	4.50E-06	0.1046
2	6.66E-06	0.23846
3	1.25E-05	0.38832
4	0.86139	6.1425

Figure 13 shows the mode shape for the first four modes of the frequency response of free vibration with Pre-stress. Furthermore, Figure 14 shows the cumulative percent of the mass contribution for each mode in the Model C6 upon the vertical, horizontal, and rotational directions. If the superposition principle is used, it is possible to use the first two modes that provided 80% of the amount of mass participation. And a summary of the frequency responses of the six case studies illustrated in Figure 15. It is educed from Figure 15 that in the case of Pre-stress conditions, mass matrix, and stiffness matrix cause reduced the stiffness and frequency.



1st mode 2nd mode



3rd mode 4th mode

Figure 13. Mode shapes of Model C6 in the first four modes

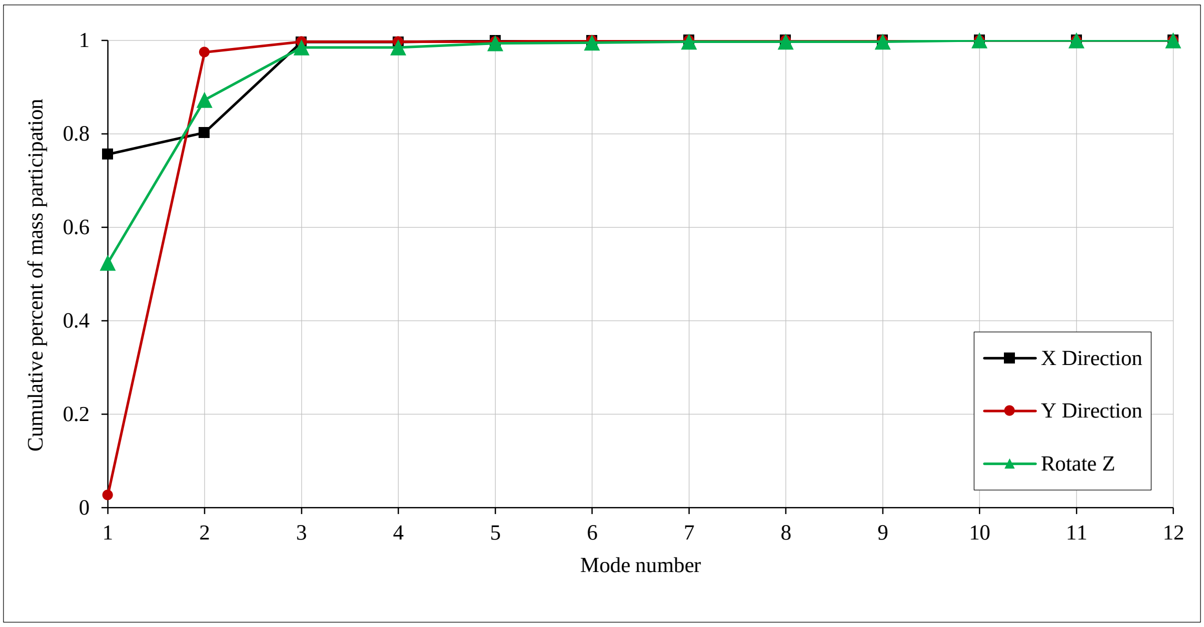


Figure 14. Cumulative percent of the mass participation in the each mode of Model C6

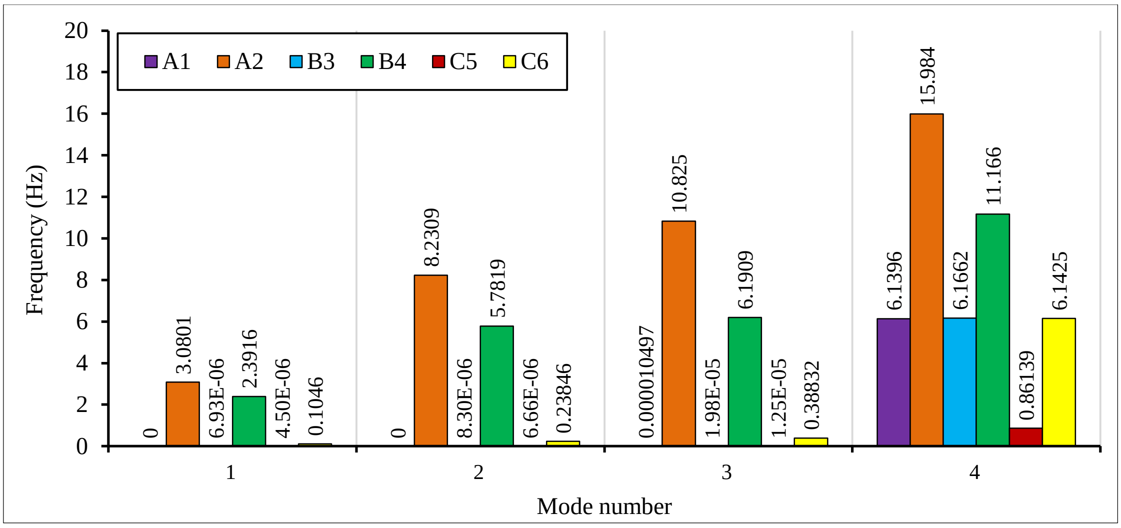


Figure 15. Comparison of the modal frequency of the specimens

6. Conclusion

A parametric study of the effect of different conditions on the frequency behavior of the dam was investigated by using the FEM. Initially, due to the effect of discretization and dimensions of the elements on the stiffness and softness of the model, the effect of the mesh size on frequencies was investigated to optimize the dimensions of mesh based on grid independence. RSO method confirmed that has a proper capability to appraise parametric and sensitive analysis in order to achieve the optimum element size remarked by the grid independence concept. Error Contour method was used to investigate the energy variation of adjacent elements in the optimized element size. The results exposed that the RSO method has an appropriate application to attain minimum energy difference and consequently, the quality of the grid meshing is acceptable and the responses will be accurate.

According to the analyses, appraisement of the results revealed that the Pre-stress condition as an IC caused increasing the modal frequencies. Moreover, by decreasing in foundation stiffness and increasing the mass, frequencies in case of with Pre-stress decreased and in case of without Pre-stress has more decreased. Therefore, it can be deduced that for accurate analysis of the dam-reservoir-foundation model analysis, it has been necessary to consider the exact BC and IC to assess the model with a proper viewpoint.

7. Conflicts of Interest

The authors declare no conflict of interest.

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