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Seismic Response Analysis of Concrete Gravity Dams Using ABAQUS

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ABSTRACT

Extensive study is currently being conducted on the safety of existing dams against seismic stresses and the design of new dams that can withstand earthquakes. The design and safety evaluation of earthquake-resistant dams relies on a dependable analytical approach that can accurately determine the stresses and deformations caused by earthquakes. Hence, this study aims to conduct a modal analysis, examine the impact of hydrostatic forces, and assess the effects of dynamic loads on the dam with both rigid and flexible foundations using ABAQUS. The current study used the ABAQUS software to do modal, static, and dynamic analysis of the Koyna dam in Maharastra, India. The dam is subjected to dynamic analysis in two scenarios: one with a hard basis and the other with a flexible base.

1. INTRODUCTION

A dam functions as a barrier constructed/built throughout the stream or river to control water, raising of the water level behind it, and creating a reservoir that is used for electricity generation, flood control, irrigation, & water supply. Failures in these structures can lead to property loss and environmental damage, especially when seismic activity induces cracks within the dam. Hence, it is crucial to assess dam stability against various forces, including hydrodynamic forces and earthquakes.

The initial approach to analysing the seismic behaviour of rigid concrete gravity dams was proposed by Westergaard, while Chopra furthered this method by considering an inclined upstream face for a more accurate representation. The safety of existing dams & the design of new dams that can resist the earthquake have been the focus of extensive research in recent decades, with significant studies aimed at understanding dam behaviour under seismic loads.

The introduction of the finite element method (FEM) became prominent due to its advantages over established methods, offering more accurate results. Initially assuming incompressible water, later studies highlighted the importance of water compressibility in seismic analysis. Researchers like Fenves & Chopra, Chopra & Chakrabarti, and Hall & Chopra explored finite element evaluation/analysis using the natural frequency obtained, while Sharan, Sommerfeld, Maity & Bhattacharya, and Tsai & Lee developed various boundary conditions.

Soil type plays a significant role in a dam's response, and Pal conducted the first nonlinear evaluation/analysis on the Koyna dam, neglecting reservoir effects and assuming a rigid foundation. Khosravi and Heydari analysed dams under different conditions, considering empty and full reservoirs and flexible or rigid foundations. Burman et al. and Reddy et al. explored the impact of foundation flexibility and nonlinearity on seismic responses, utilizing SAP 2000.

This paper focuses on analysing a dam structure, excluding the effect of reservoir water that incorporates influence of geotechnical/soil conditions.

Table 1. Material Properties for dam (concrete gravity) and foundation/soil

Material	Young's modulus (MPa)	Density (kg/m^3)	Poisons ratio
Concrete	3.15mpa	2430	0.235
Foundation soil	6.8923mpa	981	0.333

2. METHODOLOGY

2.1. Description of dam (Concrete Gravity Dam)

In the research study, modal, static(Stable), and dynamic analyses of the Koyna Dam that is concrete gravity dam, located in Maharashtra, India, were conducted using ABAQUS 2016 software for both rigid foundation & flexible foundations. The Koyna Dam stands at a height of 105 m, having a crest width of 15 m, a length of 900 m, and a base width of 75 m. The dam's capacity is 2797.4 Mm³. Table 1 summarizes the properties of material of the dam(concrete) & soil employed for the estimation of loads and dam behavior under various loading condition.

To capture soil-structure interaction, the analysis includes a soil domain with a depth of 310 m. The North-South Component of the El Centro earthquake data were employed to evaluate the results in this study. The earthquake had a magnitude of 6.9 on the Richter scale & an highest intensity of X (Earthquake acceleration in horizontal Direction) on the Mercalli intensity scale.

2.2. Static and dynamic(seismic) analysis of DAM in ABAQUS

In the structural evaluation using ABAQUS, the initial step involves creating a geometric model based on the dimensions of the Koyna Dam (Maharastra, India) used in the present study. Geometric model/Dimension of the Koyna Dam is depicted in Figure 1. Following the model creation, material properties that are specified in the Table 1. Subsequently, the parts of dam are assembled using the assembly function in ABAQUS, and the appropriate type of structural estimation/evaluation is selected through the step module of ABAQUS.

The Mesh generation (Meshing) is then performed by defining mesh properties in ABAQUS and selecting a proper element type. In this study, a four-node bilinear plane strain element is chosen, with the elements shaped as quadrilaterals. To conduct modal and hydrostatic analyses specifically on the dam structure, the dam's base is rigid or flexible. For dynamic (seismic) analysis, a Displacement/Rotation type of boundary condition is applied, with zero consideration for rotation and translational movement in vertical/upward direction. This limitation is imposed since the dam analysis focuses solely on the horizontal (X-Direction) acceleration induced by the earthquake/seismic load.

For Dam-foundation (Dam Base) interaction model, the dam is connected to the modeled soil part, and Displacement/Rotation boundary conditions are used to the soil domain. The dam-foundation/base interaction is established between the soil & the dam, and fixed edges are defined on the soil domain(part) except for the edge involved in that type of interaction. The interaction challenges between the soil & the structure is addressed through a surface-to-surface type of interaction, restricting sliding to a finite limit while maintaining a rough tangential behavior for the contact.

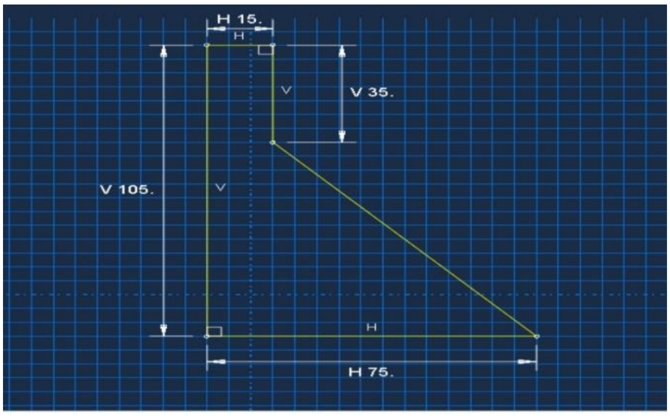


Figure 1. Dimension of dam in ABAQUS

3. RESULTS AND DISCUSSION

3.1. Modal Analysis of Dam with Rigid Foundation/Base in ABAQUS

The modal analysis was operated to determine the first ten natural frequencies & mode shapes of the concrete gravity dam utilizing ABAQUS with a rigid foundation. Dam mesh was created for 4-node Bi-linear plane strain quadrilateral elements, resulting in 85 elements and 105 nodes.

The computed frequencies with respect to mode numbers 1 to 10 are as follows: 2.9004, 7.4572, 8.2151, 11.148, 11.392, 11.627, 15.183, 17.004, 22.960, 23.962HZ through modal analysis, the first 10 mode shapes were obtained for the dam having an empty reservoir & rigid foundation. Figure 2 illustrates mode shapes 1 and 2 of an empty dam with a rigid base/foundation, as obtained in ABAQUS 2016. Notably, maximum displacement (U, Magnitude) is gained at the location of crest for mode shapes 1 to 6. As the frequency increases, the maximum deformation/displacement gradually transfer from the crest location to the base/bottom of the dam.

For lower frequencies, a uniform displacement pattern is observed, while an growth in natural frequency leads to non-uniform deformation/displacement across the dam. In mode shapes 8 and 10, the maximum displacement(Max-Deformation) was identified in the toe area of the dam.

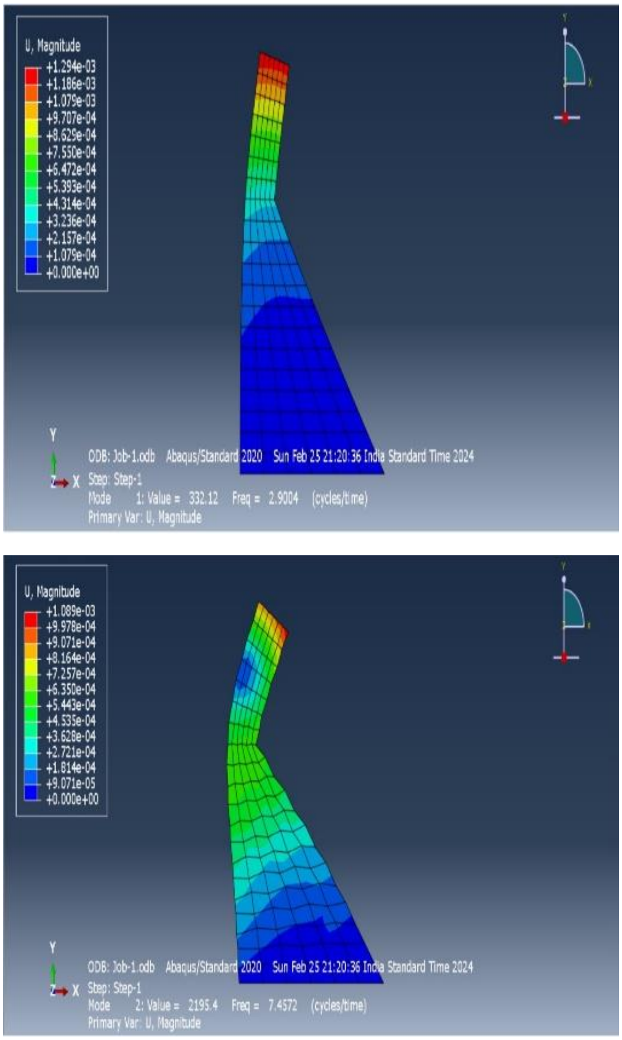


Figure 2. Empty dam with rigid base the modal shape 1 & 2 are presented.

Table 2. Natural frequency obtained from ABAQUS is compared.

Mode number	Natural Frequency(Hz)		Percentage difference [%]
	Sarkar et al 2023	ABAQUS 2016	
1	3.002	2.9004	0.03%
2	7.953	7.4572	0.06%
3	10.848	8.2151	0.20%
4	15.640	11.148	0.28%

Natural frequency of dam having rigid foundation

The above Table 2 that compares the result of 1st four frequencies that obtained in ABAQUS and literature results (Sarkar et al.23). This gives the acknowledgement about the natural frequency of dam which is achieved with ABAQUS, and researchers has similarity and conformity.

3.2. Modal Analysis of Dam with Flexible Base in ABAQUS

The modal evaluation of Dam, considering Devoid reservoir and a flexible base/foundation, was conducted, & the resulting first 10 natural frequencies were noted. The frequencies with respect to mode numbers 1 to 10 are as follows: 2.8821, 6.8745, 7.4221, 9.3730, 9.9967, 11.387, 12.683, 15.122, 18.720, 20.807HZ respectively.

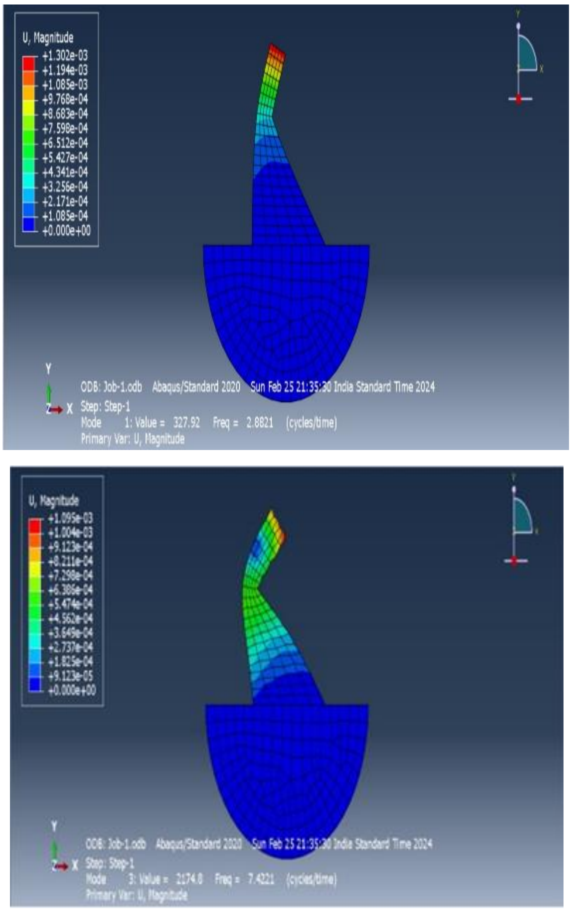


Figure 3. Empty dam with flexible base the modal shape 1 &2 are presented.

The modal analysis/evaluation of the dam with an empty/devoid reservoir and flexible base/foundation provided the corresponding first ten mode shapes Figure 3. Notably, each mode shape exhibits distinct deflections. From mode shape four to six, variations in deflection are observed throughout the dam, with minimal soil deflection. As obtained natural frequency grows in values, more significant deflection/displacement of both dam and foundation soil becomes apparent.

A comparison of mode shapes between flexible and rigid foundations reveals that the mode shapes with a flexible base exhibit more distortion compared to those with a rigid base/foundation. In the contest of a rigid base/foundation, deflection/displacement is constant on mode shapes 1 to 6. In contrast, with a flexible base/foundation, all mode shapes except mode 1 display non-uniform deflection/displacement. Additionally, the 1st natural frequency noted through ABAQUS simulation (2.8415 Hz) was compared with the literature (Chopra 1980). Natural frequency that are noted from ABAQUS closely matches the literature frequency of 2.9325 Hz that is reported.

3.3. Hydrostatic Load Analysis of Dam with Rigid Base / Foundation in ABAQUS

Hydrostatic (Water Pressure) analysis was conducted, and various stresses & deformations were observed utilizing ABAQUS 2016, with the element type and the number of modes mirroring those employed in modal evaluation/analysis. The maximum & minimum total displacement/deformation of dam was determined to be 1.011e-02 m and 0.0 m respectively. Contour map that illustrates the total deflection/deformation induced by hydrostatic pressure/load is depicted in Figure 5.

Table 3 presents the equivalent (S, Mises), major principal stress (S, Max-Principle), and shear stress (S, S12) of the dam resulting from hydrostatic pressure. Additionally, Maps of contours illustrating shear stress (S, S12) and major principal stresses (S, Max-Principle) are provided in Figure 6. The major principal stress ranged from 1.043e+05 to 1.252e+06 0 N/m², while shear stress varied from -5.718e+03 to 4.731e+05 N/m². Observing Figure 6, it is evident that the maximum shear (Max Stress) and major principal stress (S, Max-Principle) occur at the heel area of the dam, and the minimum stresses is localized within the area crest in both the cases. The variation in shear stress (S, S12) & major principal stress (S, Max-Principle) throughout the entire parts of the dam exhibits similarity.

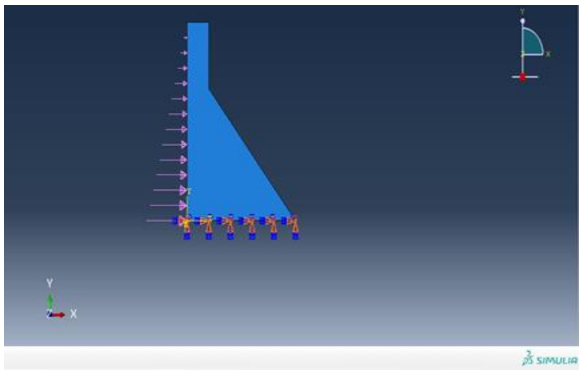


Figure 4. Hydrostatic Loading for dam having rigid foundation

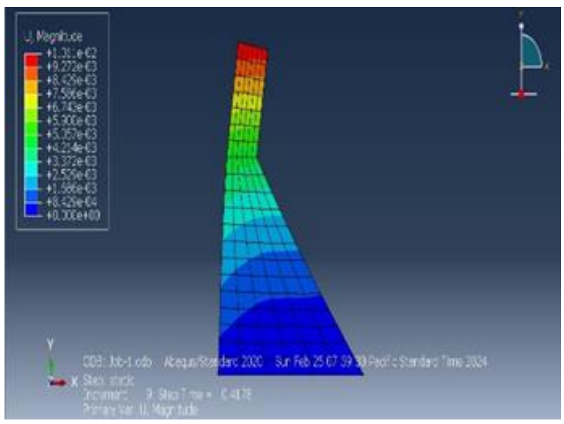


Figure 5. Displacement of dam in hydrostatic load at rigid foundation

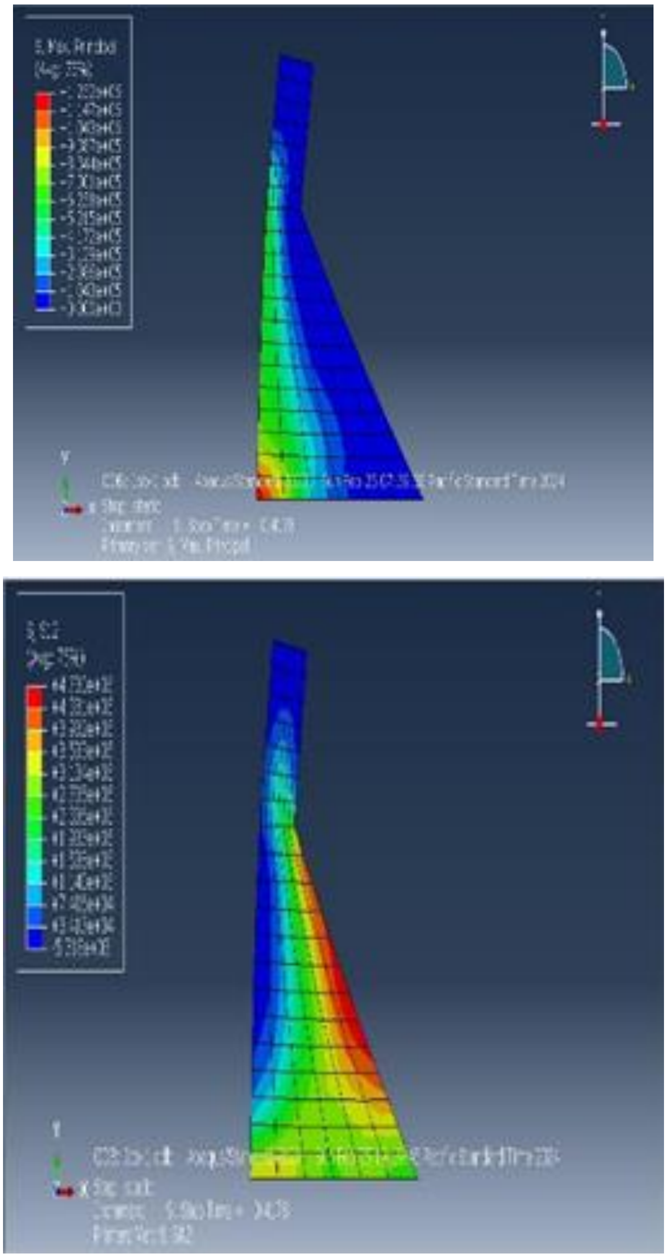


Figure 6. Shear stress (S, S12) and major principal stress (S, Max-Principle) of dam under hydrostatic load on rigid foundation.

3.4. Hydrostatic (Water Pressure) Analysis of Dam with Flexible Base/Foundation

The hydrostatic structural evaluation of dam with a flexible base/foundation for deflection is depicted in Figure 6. In the case of a flexible foundation, crest of the dam experiences a deflection of 1.695e-02 m, which is larger value in comparison to the deflection of the crest with a rigid foundation (1.011e-02 m). The maximum deflection/displacement occurs in the crest area of the dam.

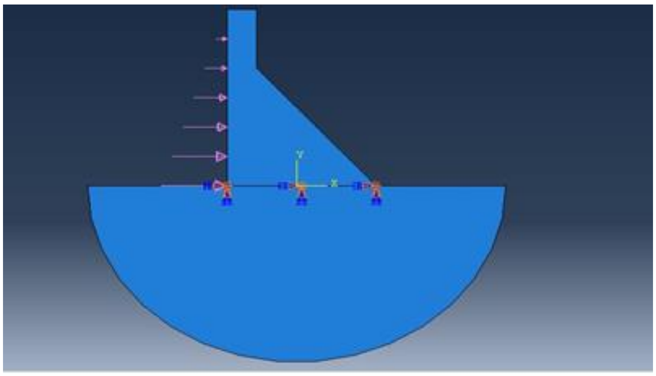


Figure 7. Loading hydrostatic pressure on dam with flexible foundation.

Major principal stress (S, Max-Principle) & shear stress (S, S12) obtained from the hydrostatic evaluation of a dam with a flexible base/foundation are illustrated in the Figure 9. The higher/maximum values for major principal stress (S, Max-Principle) & shear stress (S, S12) are 2.996e+05 N/m², and 1.138e+05N/m2, respectively. It also can be evident from Figure 9 that the maximum major principal stress (S, Max-Principle) & shear stress (S, S12) are seen at the heel area of dam. Minimum stress data is gained in the crest area of the dam, likely to be same with the dam having a rigid base/foundation.

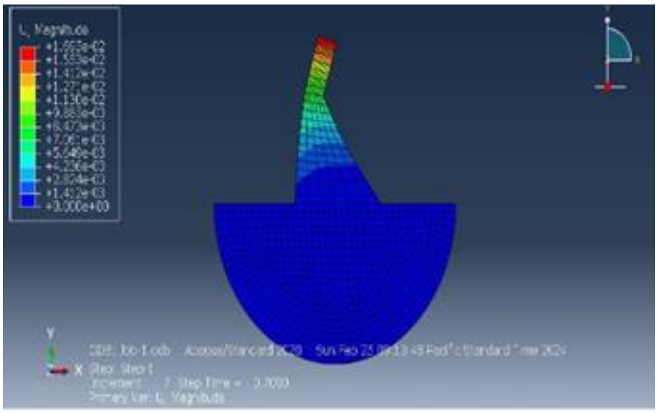


Figure 8. Displacement of dam due to hydrostatic pressure having flexible foundation

Comparison of results between rigid and flexible foundation under hydrostatic pressure

Maximum displacement, major principal stress (S, Max-Principle) & shear stress (S, S12) of dam are compared having rigid foundation and flexible foundation under hydrostatic pressure.

Table 3. Shear stress (S, S12) and major principal stress (S, Max-Principle) are presented for rigid foundation for hydrostatic load in contour map

Parameters	**Equivalent (S-mises) stress (N/m^2)**	**Major principal stress (S, Max-Principle) (N/m2)**	**Shear stress(S, S12) (N/m2)**	**Displacement (m)**
Minimum	1.283e+03	1.043e+05	-5.718e+03	8.429e-04
Maximum	1.331e+06	1.252e+06	4.730e+05	1.011e-02

Table 4. Shear stress (S, S12) & Major principal stress (S, Max-Principle) are presented for flexible base/foundation due to hydrostatic(water) pressure in contour map.

Parameters of comparison	**Equivalent (S-mises) stress (N/m2)**	**Major principal stress (S, Max-Principle) (N/m2)**	**Shear stress (S, S12) (N/m2)**	**Displacement (m)**
Minimum	2.654e+05	2.496e+05	-9.560e+03	1.412e-03
Maximum	3.185e+06	2.996e+06	7.924e+05	1.695e-02

Table 5. Maximum displacement, Shear Stress, major principal stress are presented for flexible base/foundation

Case N0.	**Foundation/Base condition**	**Max displacement**	**Major principal stress (S, Max-Principle) (N/m2)**	**Shear stress (S, S12) (N/m2)**
1.	Rigid base	1.011e-02	1.252e+06	6.793e+04
2.	Flexible base	1.695e-02	2.996e+06	3.185e+06

Table 6. Maximum displacement, major principal stress (S, Max-Principle), & shear stress (S, S12) under seismic load.

Case N0	**Foundation /base condition**	**Maximum displacement(m)**	**Major principal stress (S, Max-Principle) (N/m2)**	**Shear stress (S, S12) (N/m2)**
1.	Rigid	1.593e+00	6.084e+08	9.870e+7
2.	Flexible	2.859e-01	8.013e+07	1.964e+07

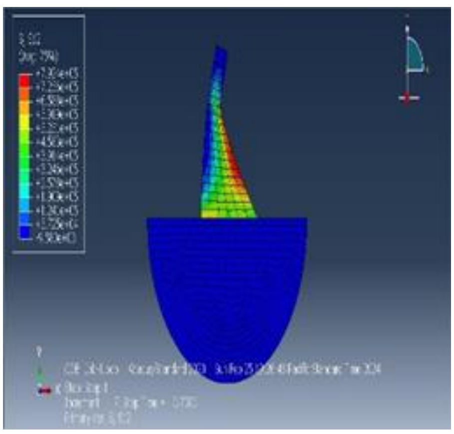
3.5. Dynamic Analysis

The dynamic(seismic) analysis of the dam is conducted using El Centro earthquake experimental data, and various dam literature reports, including displacement/deflection, major principal stress (S, Max-Principle), & shear stress (S, S12), are determined using ABAQUS 2016. The dynamic(seismic) analysis is performed under 2 conditions: a dam with the rigid base/foundation & a dam with the flexible base/foundation. The Dam's rigidity is established by fixed condition at the base. Table no. 4 presents data for different dam behavior under rigid & flexible conditions to the time step of 1 second. Grater values of displacement/deflection & stresses are determined in the condition of a rigid foundation/base compared to a flexible base/foundation for the dam in Table no. 5.

The modelling of the given dam for seismic analysis the following properties of concrete gravity dam is assigned in ABAQUS using concrete damage plasticity in mechanical property of a material.

- Density =2430 kg/m^3
- Modulus of elasticity=3.15mpa
- Poisson ratio=0.33
- Delegation angle=36.61
- Compressive initial stress=13.0mpa
- Compressive ultimate stress=2.41mpa
- Tensile failure stress= 2.9mpa
- Damping width β=0.00323

Figure 10 illustrates the total deflection/displacement of Dam with both rigid & flexible foundations/base in 10 seconds because of the dynamic(seismic) load. The maximum deflection/displacement is observed in the crest area for both rigid and flexible foundations during time steps such that 1.76s & 1.011 seconds respectively. In case of a rigid base/foundation, the maximum displacement/deflection is consistently in the crest area for all the available time steps. Conversely, for a flexible base/foundation, the maximum deflection/displacement occurs in the central structure of a dam at time-steps 1.762s and 1.011 seconds and at the base of the dam at the 10-second time-steps.



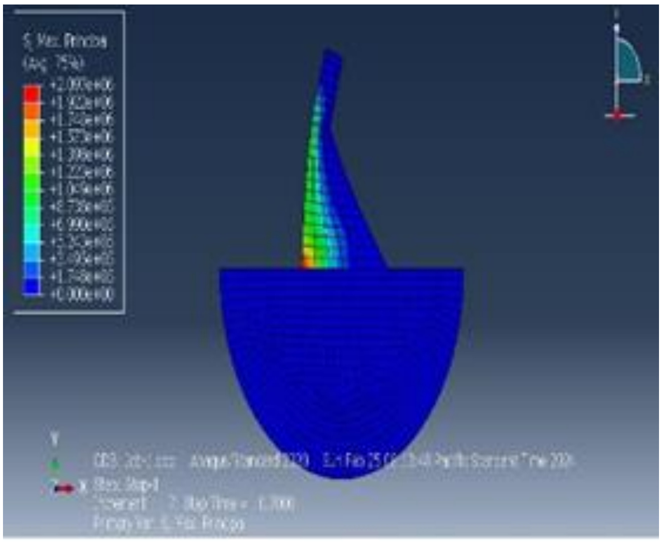


Figure 9. Shear stress (S, S12) & Major principal stress (S, Max-Principle) of dam in hydrostatic pressure on flexible foundation.

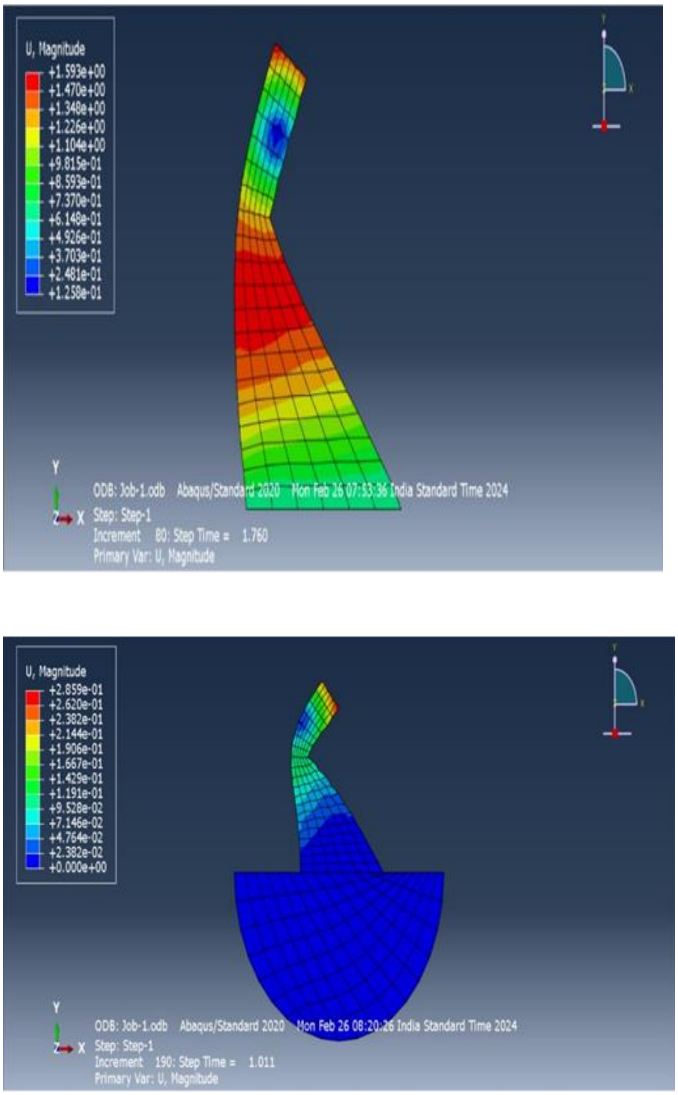


Figure 10. Displacement of rigid & flexible base/ foundation at 1.76s & 1.011 respectively.

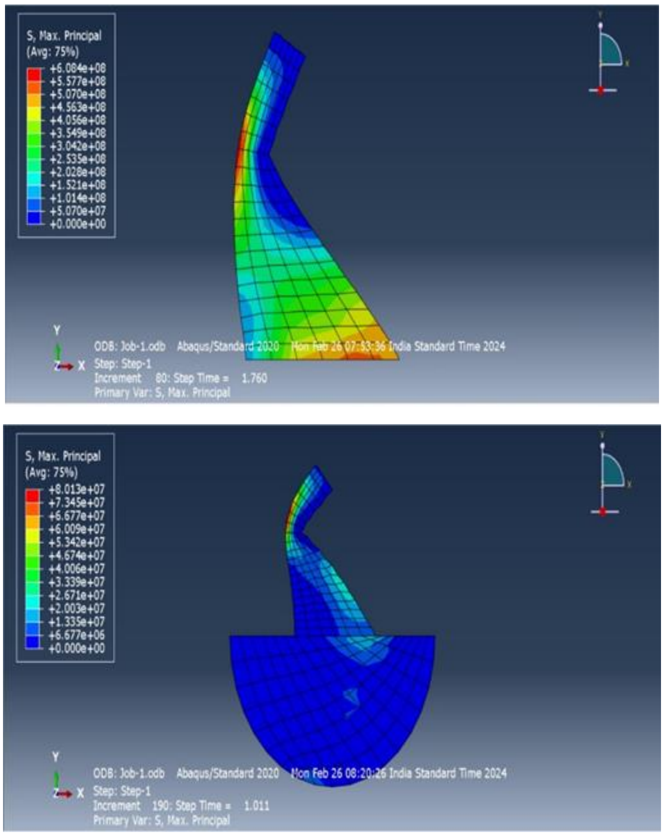


Figure 11. Major princpal stress (S, Max-Principle) of rigid & flexible base/ foundation at 1.76s & 1.011 respectively.

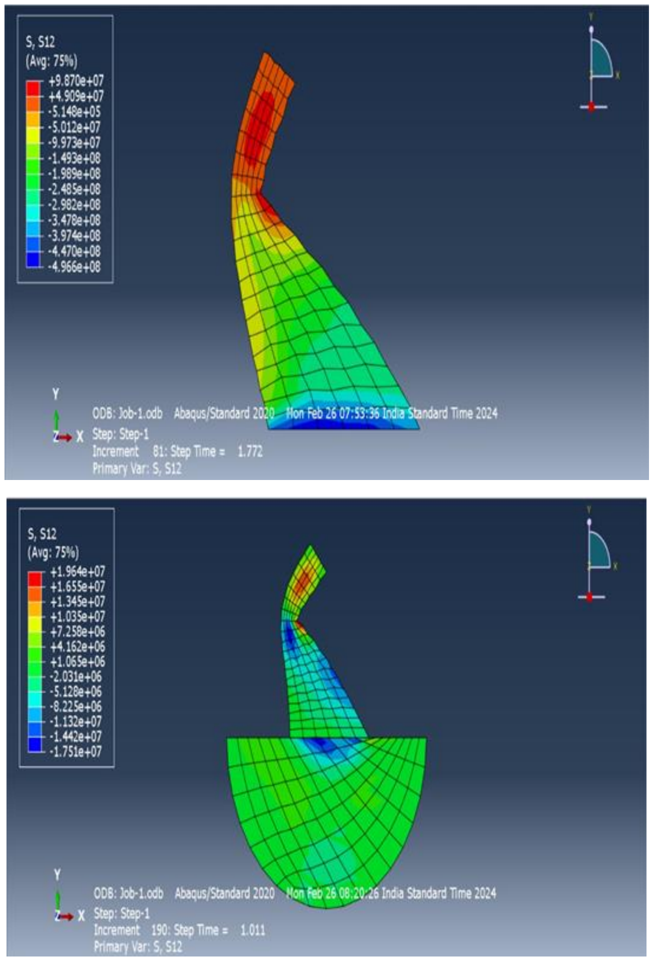


Figure 12. Shear stress (S, S12) of rigid & flexible base/foundation at 1.76s & 1.011 respectively.

The major principal stress (S, Max-Principle) is to be developed in the body parts of the dam because of the dynamic(Seismic) pressure is computed using El Centro earthquake data with an equivalent time difference of 0.01 seconds. Contour map of major principal stress (S, Max-Principle) for rigid & flexible foundations at a time-step of 10 seconds is represented in Figure no. 11. The appearance pattern of the major principal stress (S, Max-Principle) changes for each time-step for the both rigid foundation and flexible foundations. Major principal stress's contour map for a rigid base/foundation differs from that of a flexible base/foundation. Major principal stress (S, Max-Principle) is observed in the heel area of the available dam in the case of a rigid base/foundation, whereas in the central structure of the modeled dam for a flexible base/foundation at the 10 second time-step.

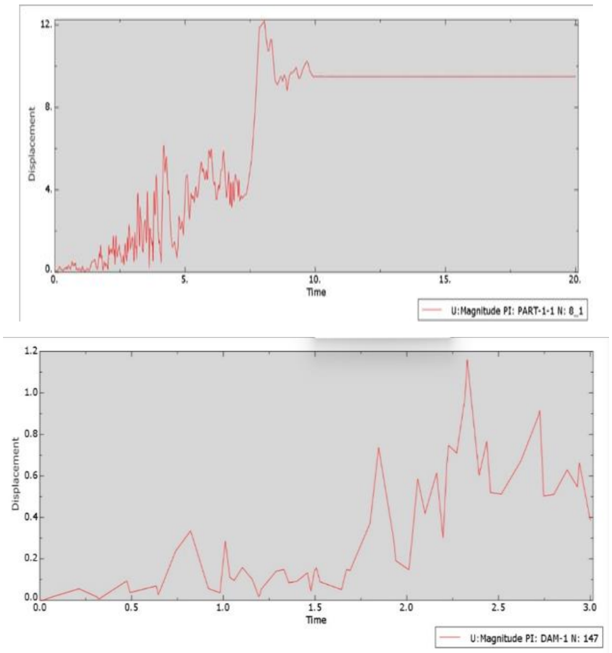


Figure 13. Displacement graph of rigid & flexible base/foundation at 1.76s & 1.011 respectively.

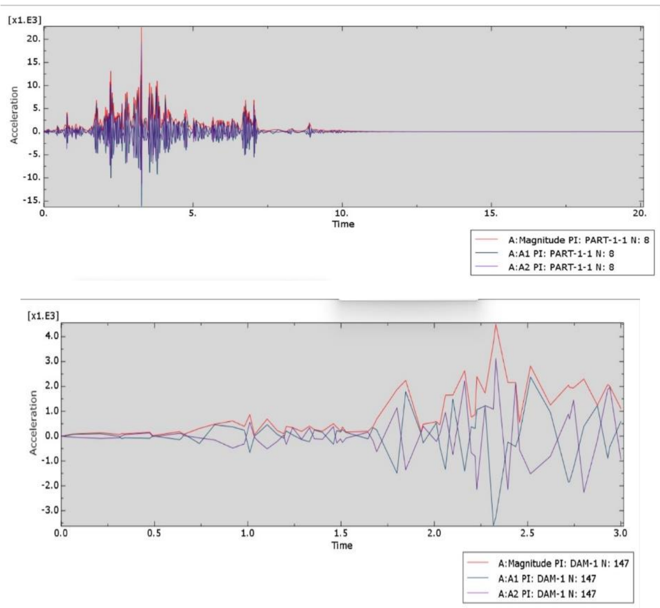


Figure 14. Seismic graph of rigid & flexible base/ foundation at 1.76s & 1.011 respectively.

3.5.1. Graph discussion

The displacement and ground acceleration of concrete gravity dam is compared with graph under seismic load having rigid foundation and flexible foundation. The results and the differences can be observed by the above graph (figure 14). The graph is plotted with the same note and same time steps. Seismic graph is presented in fig 14 for rigid & flexible base respectively and displacement at node no.8 the graph is presented in fig 13 respectively.

3.5.2. Comparison of results between rigid and flexible foundation under seismic load

Maximum displacement, major principal stress (S, Max-Principle) & shear stress (S, S12) of dam are compared having rigid foundation and flexible foundation under seismic load. The data obtained are presented in the following Table 6.

4. CONCLUSION

This study target to assess the behavior of a dam (concrete gravity dam) with both rigid & flexible base/foundations using ABAQUS. The results that are gained from modal analysis have been compared with the existing literature reports to validate the efficiency of the research work. Subsequently, an interaction model is developed, and dynamic(seismic) analysis is performed with ABAQUS 2016.

Since the frequency raised, the maximum deflection/displacement gradually changes/transfer from the crest area to the base area of dam. Constant displacement (Uniform Deflection) is gained for low frequencies, whereas raise in the natural frequency leads to non-uniform displacement/deflection throughout dam.

Hydrostatic effect in the crest area of the dam experiences a displacement/deflection of 1.695e-02m in case of a flexible foundation/base, which is larger that is compared to deflection/displacement of crest with a rigid base/foundation (1.011e-02 m). The values of major principal stress (S, Max-Principle) & shear stress (S, S12) are higher with a flexible base/foundation that is compared to a rigid base/foundation. Specifically, the major principal stress (S, Max-Principle) of dam is lower (1.252e+06N/m2) with a flexible base/foundation, that is compared to a rigid base/foundation (2.097e+06 N/m²). On the other hand, the shear stress (S, S12) of dam is higher with a flexible base/foundation (7.924e+05N/m²) compared to a rigid foundation (4.730e+05N/m²).

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