Investigating the Effect of Longitudinal Gallery on Dynamical Response of Gravity Concrete Dams Using FEM

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Abstract

The aim of this study was to consider the necessity of study and considering different dimensions of existence galleries in gravity concreted dams by paying attention to design limitations and based on dam's sustainability provision. In recent years, structural optimization has been studied extensively with various considerations. Concrete volume in concrete dams is higher than other concrete dams. Therefore, if the concrete volume of these dams can be reduced without reducing the dam's safety and stability, the costs of constructing such dams could be significantly reduced. For this purpose, in this paper, the Pine Flat Gravity Dam has been selected, its numerical model has been constructed and stimulated under the Taft earthquake. There are three types of small, medium and large size galleries in different positions. The dam reservoir and foundation in the current study has been modeled and the foundation has been assumed to have no mass. Then the results have been examined. Finally, it can be concluded that while the medium gallery was in the middle of the dam, the optimum condition for reducing concrete was achieved by maintaining the stability of the dam.

Keywords: Gravity concrete dams, Finite Element Method, Longitude gallery, Dynamical analysis

1. INTRODUCTION

Achieving an optimal design has always kept designers busy, so one of the most important tasks of a design engineer is to make the best design with sufficient safety and cost among the many designs with different shapes for a particular structure to choose from other designs. Gravity concrete dams are generally more economically viable and easier to implement than other types of concrete dams. Sometimes it is more suitable and economical than some places, such as relatively narrow valleys or steep valleys, and even sometimes the soil is not suitable and sufficient for the construction of earthen dams. The gravity dam may fail for one of three reasons: (1) sliding on a horizontal plate, (2) rotate on the toe, (3) Weakness of building materials (increased stress than allowed stress). Dam failure is generally due to the development of upward tensile cracks or the loss of materials which increase the compressive stress downstream [11].

The aim of this study was to investigate the necessity of studying and optimizing science as well as investigating various optimization methods and investigating different shapes of holes in the gravity of concrete dams' body considering design constraints and based on dam stability. In recent years, optimization of the structure has been thoroughly studied with respect to the structure. Concrete volume is higher in gravity concrete dams than other concrete dams, while durability of dams is higher than other types of concrete dams and their cost of protection and maintenance is lower. Also, gravity concrete dams have easier construction and design than other types of concrete dams. Therefore, it is important to use these dams.

Many issues in various fields have been successfully resolved using FA and its variants. (Maghlani, GholiAbadi and Rahnama 2013, Farhodnia, Mohammad, Sharif Zayandeh Rudi 2014, Mister, Meister, Young and Brest 2013, Gomez 2011, Miguel and Fadi Miguel 2013, Yang 2013) [2, 3]. The use of this meta-heuristic algorithm in optimal design of dams has been reported so far. A relatively new optimization approach is currently used in some engineering problems. (Baghlani and Maki Abadi 2013; Maki Abadi, Taalani, Rahnama and Hadianfar 2013, Niknam, AziziPanah, Abroghi and RasoolNarimani 2013) [4, 5, 6]. Optimal design of gravity dams is a relatively complex approach because many factors such as fluid and structure interaction have to be taken into account.

2. NUMERICAL MODELING

The necessity of designing gravitys is to know the forces applied to stress and structural stability. Figure 1 shows the forces acting on the gravity barrier [7].

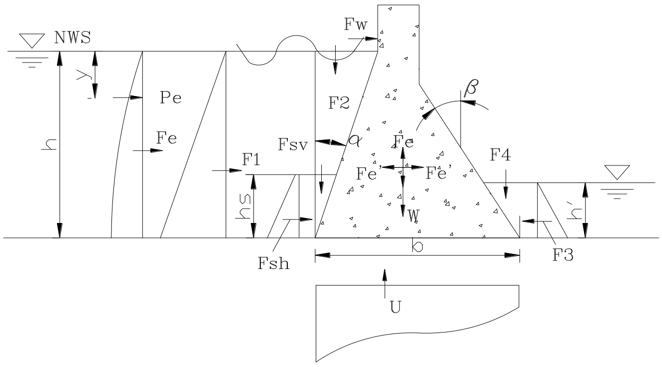


Figure 1: The forces acting on the gravity concrete barrier

All seismic analyzes were performed using ANSYS, version 11.0, finite element software. In order to mesh the main body of the dam and foundation, the 8 node SOLID45 cube element with three degrees of transient freedom has been used in each node. The schematic overview of these elements is shown in Figure 2 [8].

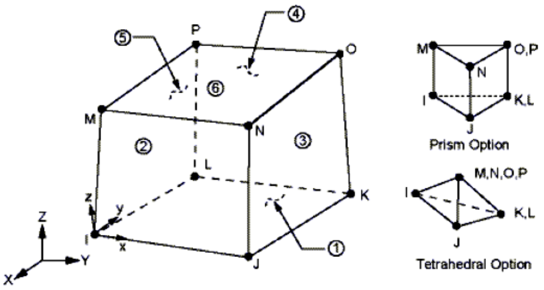


Figure 3: Schematic of Fluid30 cubic elements

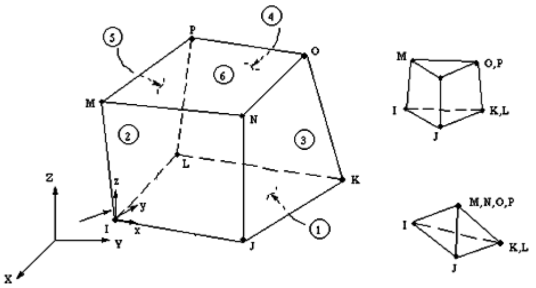


Figure 2: Overview of Solid45 cubic elements

In the model of the reservoir, eight-node FLUID30 cubic elements have three degrees of freedom and one degree of pressure freedom per node (Figure 3). The pressure at the free surface of the tank was assumed to be zero. The boundary conditions of the bottom of the reservoir have been taken into account for complete absorption of the hydrodynamic wave.

It should be noted that the properties of the materials vary in the dynamic region, That is, some properties of concrete and foundations underwent rapid loading. Based on valid references and available experience, the coefficients considered for the various parameters in dynamic analysis are presented in Table 1 [9].

Table 1: Parameters considered for dynamical analysis

Parameter	applied coefficient	The intended value
Specific gravity of concrete	1	2400 kg/m3
Modulus of elasticity of concrete	1.15	46GPa
Poisson concrete coefficient	0.7	0.14
P deformation modulus	1	15GPa
P Poisson's coefficient	1	0.25
pushing resistance	1.15 as the dynamic gain coefficient and 1.1 as the coefficient of confidence	36.5MPa
Tensile strength	1.50 as the dynamic gain coefficient and 1.0 as the coefficient of confidence	5.1MPa

The effect of the dam-lake interaction was added to the equation of motion as an additional force vector [6]:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{f_t\}+\{q_t\} \tag{1}$$

The effect of the dam-lake interaction was fully applied to the force vector of {qt} which affected the upstream surface of the dam. At first, it was assumed that the tank floor was rigid to calculate the effect of dam and lake interaction on finite element method. This assumption would produce unrealistic forces. For proper estimation, the absorption effect of the tank floor should also be considered. In 1984, Fenves and Chopra also published their results, which included the effect of sediment on the bottom of the reservoir [10]. The differential equation governing dam reservoir behavior (Euler relation) was as follows [11]:

$$\rho \frac{d\vec{v}}{dt} = -\vec{\nabla} p + \vec{B} \tag{2}$$

In which ρ is fluid density, $\vec{v}$ is velocity square, p is pressure, $\vec{B}$ is Vector of forces applied to the fluid element and t is time introducer. In this regard, due to the large volume of the lake, the effect of fluid adhesion or viscosity and the boundaries of the lake on fluid behavior have been ignored. According to the following figure for the dam-lake system, it is observed that to solve the equation governing the lake in two-dimensional space, four boundary conditions have been defined which are: 1- Dam border and lake, 2- Fluid boundary and lake bed, 3- Free surface fluid boundary and 4- Lake boundary and far end [12].

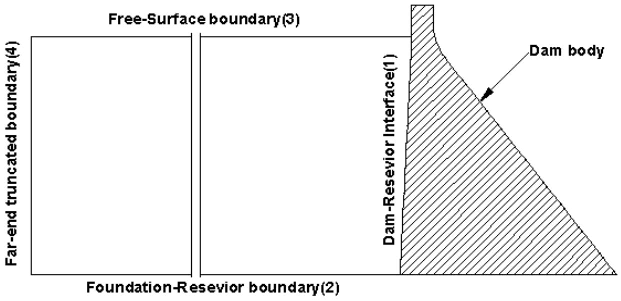
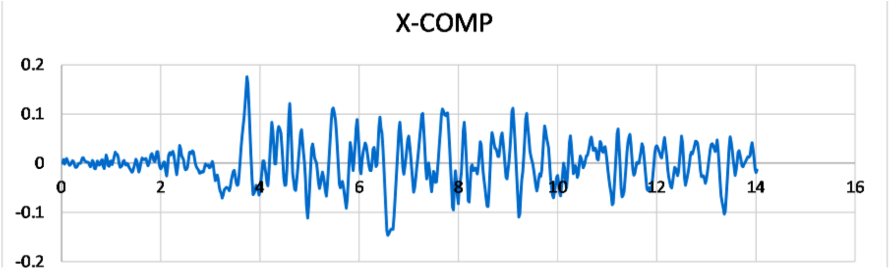


Figure 5: Dam and lake system with different lake boundaries

For the static and dynamic analysis of the dam, a three-dimensional finite element model of the dam and the pond was taken into account by the lake and the ANSYS program was applied. The composition of loading intended for dynamic analysis was as follows: Dead load (Structure Gravity) + Hydrostatic Load in Normal Tank Level (NHWL) + Sediment Load + Seismic Load

It should be noted that for the dynamic loading of these models, the Taft earthquake record has been used in two directions as shown in the figures below. The earthquake lasted 12 seconds, with its maximum acceleration based on the Earth's gravity intensity scale of 0.18 ° and because it was used in Chopra's paper, it was also utilized in our research to validate the numerical model.



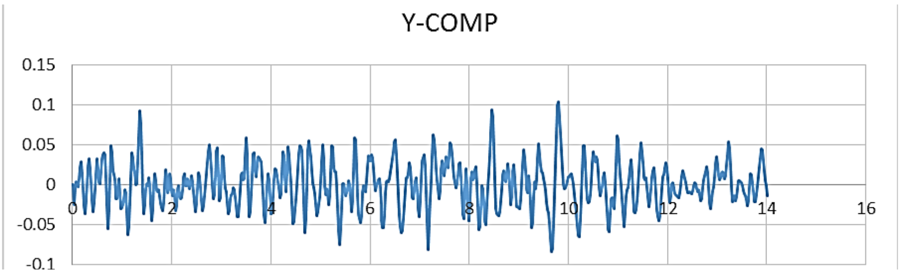


Figure 6: The horizontal and vertical components of the TAFT earthquake

3. The results of numerical analysis

The purpose of this study was to investigate the effect of gallery in the dam body on its structural performance. The gallery, on the one hand, reduced the volume of concrete that reduced the cost of its construction, but on the other hand, it reduced the cross-section and changed the hardness of the dam body, which also affected the stability of the dam. Therefore, in order to study this phenomenon, it was necessary to first develop an accurate numerical model so that it could be used to investigate the effect of the gallery according to its results.

Hydrostatic load was assumed to be in the normal level of the reservoir, which corresponded to summer conditions. To ensure the calculation of the hydrostatic force, the hydrostatic pressure in the upper body procedure was compared with the results of the manual analysis of the pressure relationship, which showed the accuracy of the calculations in the ANSYS program.

$$P = \rho.g.h = 1000*9.81*116 = 1.14MPa$$

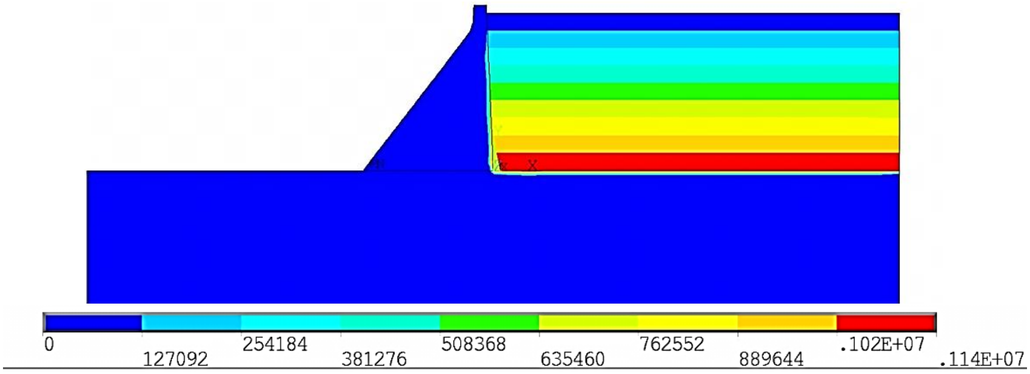
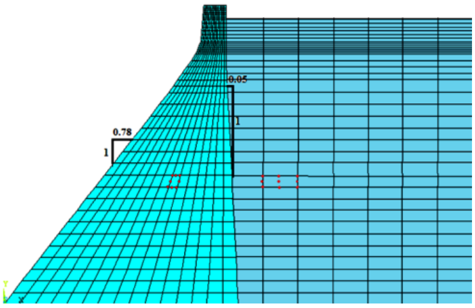


Figure 6. Hydrostatic pressure diagram

To investigate this effect, two models were constructed from the Pine Flat Dam and loaded under the dynamic load of the Taft earthquake.



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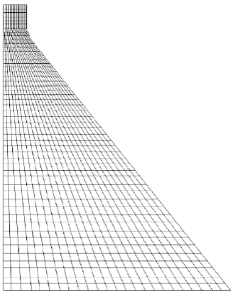

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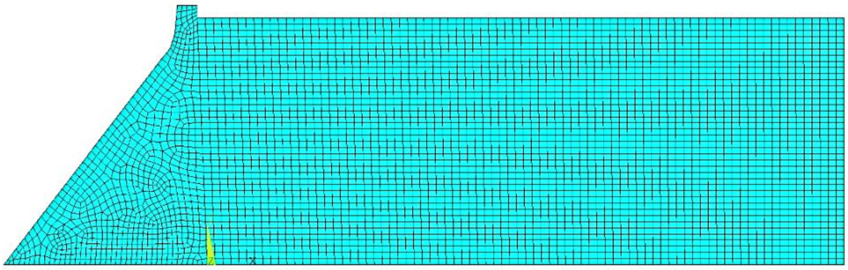

C

Figure 7: The modeling of (a) Chopra, (b) Navaia, et al.

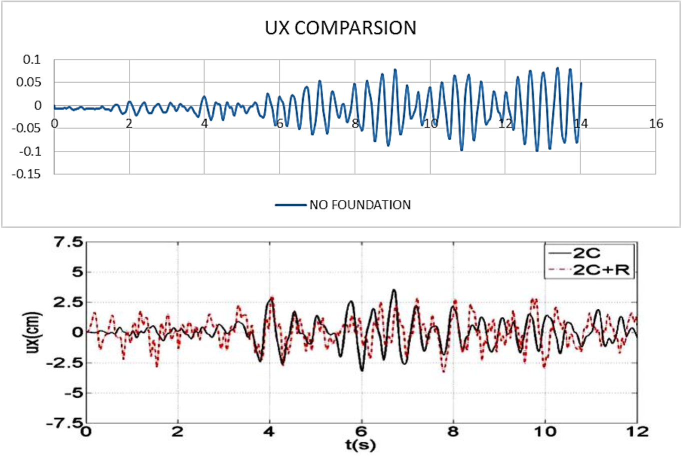

Figure 8: Comparison of the response of the present model with the results of NavaiNia et al. [13]

By comparing the above results, it can be concluded that the model of this study was in good agreement with the model of NavaiNia et al. The only difference in the results was the difference in PGA record, because the scaled record was used in NavaiNia et al.'s paper since both models were linear and scaling a record can only be achieved by multiplying it by a fixed number, therefore, it can be concluded that if the scaled model has been used, optimal results would be obtained. Since considering the work of Pi was a well-established assumption, the following models were used to examine the gallery effect. To investigate the effect of the gallery, three different gallery sizes and 3 different locations of the Pine Flat Dam with modeling of the dam foundation have been considered.

- **Small gallery**

This gallery has a radius of 10 meters located in three positions near the toe, near the heel and in the middle of the wake and the whole model has been subjected to vibrational dynamic loading that is considered the crest displacement response in two directions to compare their effects. Initially, the body of the dam is shown with its gallery.

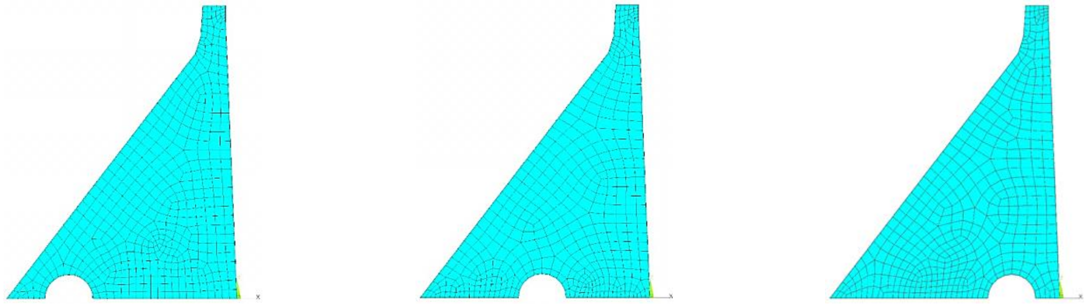

Figure 11: Stacked models for small gallery mode

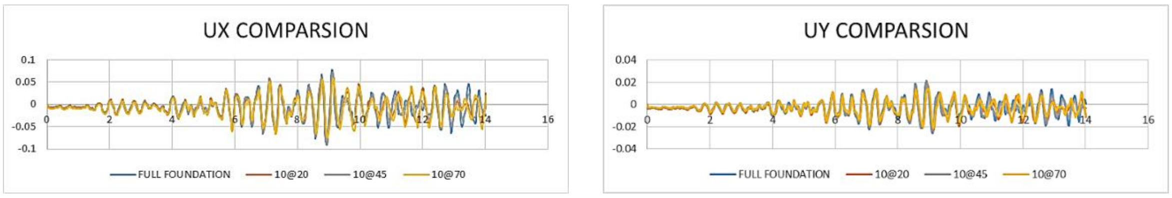

Figure 12: Comparative diagram of displacement of small gallery dams

It can be seen that in the presented models, the oscillation amplitude was about 15 cm in horizontal direction and 5 cm in vertical direction. Also according to the same approximate loading and geometry, similar behavior was observed between the models which was not unexpected.

According to the above diagrams, it can be concluded that the existence of a gallery with a radius of 10 m at the bottom of the dam body had little effect on the vibration level of the dam, and according to these results, even the presence of this gallery size limited the vibration amplitude of the dam body and improved seismic performance of the dam.

Table 2: Overhead dam crest fluctuations in different small gallery positions

	Model without gallery	10@20	10@45	10@70
Upward movement (cm)	-0.0885204	-0.0788251	-0.0913045	-0.0754746
Downstream movement (cm)	0.078924	0.0613987	0.0724221	0.0590916
Maximum vibrational amplitude (cm)	0.1674444	0.1402238	0.1637266	0.1345662

The interesting thing is that the vibration amplitude of the Touch Bar would be smaller if the small gallery was present and also, in the latter case, where the gallery was almost in the middle of the dam, the highest vibrational amplitude was observed compared to its other positions.

- **Medium gallery**

This gallery has a radius of 20 meters located in three positions near the toe, near the heel and in the middle of the wake and the whole model has been subjected to vibrational dynamic load applied to compare the impact of the dam crest displacement response, which has taken in two directions. Initially, the only body of the dam with its gallery is displayed.

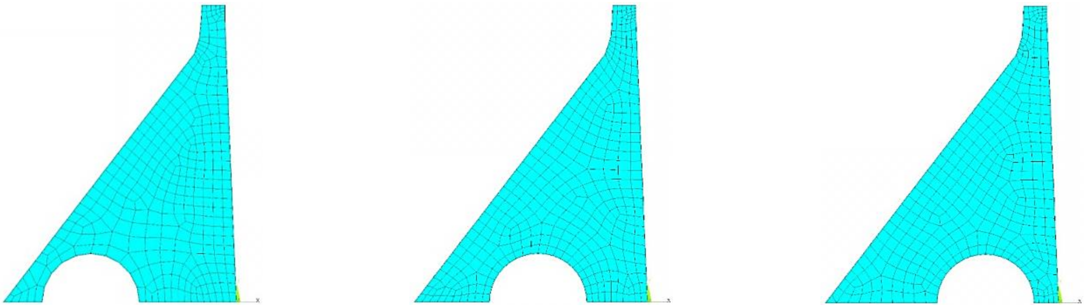

Figure 13: Stacked models for medium gallery mode

Following the loading of the dam crest under loading, it is presented in two horizontal and vertical directions to investigate the effect of suitable gallery location. For this purpose, the front displacement and the highest point of the dam crest were used.

According to the above diagrams, it can be seen that there were no noticeable changes in either the gallery that is near the heel or the middle, compared to the 10-meter gallery or the gallery without. It can also be seen that while the gallery was close to the dam claw, the oscillation amplitude had increased dramatically by about 2 times, indicating that this position was inappropriate compared to other locations.

Table 3: Overhead dam crest fluctuations in different medium gallery positions

	Model without gallery	20@30	20@45	20@60
Upward movement (cm)	-0.0885204	-0.095466	-0.072603	-0.212927
Downstream movement (cm)	0.078924	0.0779809	0.0532102	0.194547
Maximum vibrational amplitude (cm)	0.1674444	0.1734469	0.1258132	0.407474

If you use a medium gallery, you would find that if the gallery be in the middle of the dam, the vibration range would be minimal, which is even lower than when there is no gallery. Now, if a medium-sized gallery was located near the dam toe, this would greatly increase the vibrational amplitude of the dam crest, which was by no means desirable.

- **Big gallery**

This gallery has a radius of 30 meters located in three positions near the toe, near the heel and in the middle of the foundation and the whole model has been subjected to vibrational dynamic load applied to compare the impact of the dam crest displacement response, which has been taken in two directions. At first, the body of the dam is shown with its gallery.

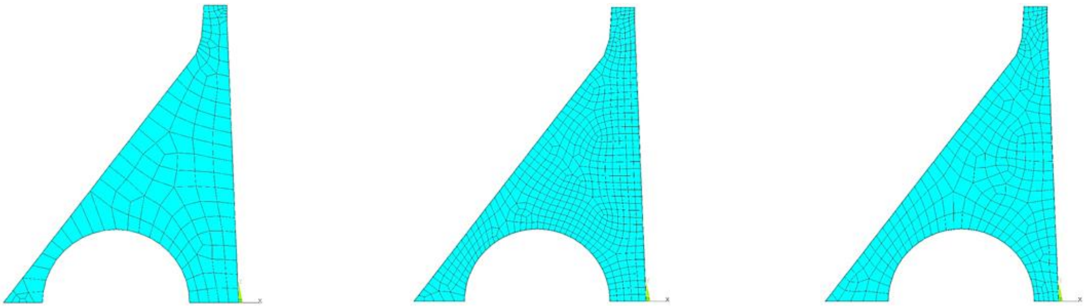

Figure 15: Stacked models for large gallery mode

According to the above diagrams, it can be seen that in a gallery with a radius of 30 meters, the position and location of the gallery did not cause a significant change in the amplitude and shape of the dam oscillation. The results also showed that at this gallery size, the closer the dam was to the toe, the lower the vibration range of the dam was. Compared to other dimensions of galleries, it can be seen that the amplitude of these fluctuations was about 2 times that of other dimensions.

Table 4: Overhead dam crest fluctuations in different large gallery positions

	Model without gallery	30@40	30@45	30@50
Upward movement (cm)	-0.0885204	-0.150769	-0.157396	-0.144888
Downstream movement (cm)	0.078924	0.141765	0.137573	0.0934683
Maximum vibrational amplitude (cm)	0.1674444	0.292534	0.294969	0.2383563

It can be seen that in the case of a large gallery and regardless of its location, the maximum vibrational amplitude for all modes was greater than that without the gallery.

4. CONCLUSIONS

Generally, the traditional design of dams is done with a trial and error process. Based on this method, an initial design is selected and dam design is analyzed. If this initial design satisfies the design requirements, the requirements would be acceptable, otherwise the modified design variables and the barrier would be re-analyzed, and the process would continue until all design requirements are met. The design of the dam is acceptable, but is not necessarily optimal. On the other hand, this process can be very time consuming. To achieve this goal more easily and safely, the use of dams' optimization techniques has become commonplace; optimal design and safe design of the dams are obtained without significantly increasing their computational and operating costs.

The presence of a gallery with a radius of 10 m at the bottom of the dam had little effect on the vibration level of the dam and, according to these results; even the presence of this gallery size limited the vibration range of the dam body, which in turn improved the seismic performance of the dam. For a gallery with a radius of 20 meters, there was no noticeable change in either the gallery near the heel or the center, compared to the 10-meter gallery or the gallery-free mode. It can also be seen that while the gallery was close to the dam claw, the oscillation amplitude had increased dramatically by about 2 times, indicating that this position was inappropriate compared to other locations. In a gallery with a radius of 30 meters, the position and location of the gallery did not cause a significant change in the amplitude and shape of the dam oscillation. The results also showed that at this gallery size, the closer the dam claw was, the lower the vibration amplitude of the damwas. In comparison to other dimensions of galleries, it can be seen that the amplitude of these fluctuations was about 2 times that of other dimensions.

Finally, it can be said that as much as possible to reduce the volume of concrete, provided that the amplitude of the vibrations not be significantly increased, the desired design would be a more optimal design, which can be deduced from Tables 2, 3 and 4 when the medium gallery was in the middle of the dam, optimum condition could be achieved.

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